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# RESEARCH ON AN ELECTROSTATICALLY FOCUSED KLYSTRON


*by D. G. Dow and R. J. Butwell*



Prepared under Contract No. NAS 1-3972 *by*
VARIAN ASSOCIATES
Palo Alto, Calif.
*for*

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# I. SYNOPSIS

This report describes a one year research program conducted under contract NAS1-3972 with National Aeronautics and Space Administration, Langley Research Center. This was a research contract having as its ultimate goal a variable output, high efficiency, electrostatically focused klystron. The klystron was to operate with high efficiency at power levels between 1 and 100 watts output, having a 10 megacycle instantaneous bandwidth at 2295 Mc, to be fully electrostatically focused. During this one year period, the following items were achieved.

(1) Electrical design of a tube intended to meet all of the required specifications.

(2) Electrical and mechanical design of a prototype which was to serve as the R and D vehicle for proof of the configuration.

(3) Detailed laboratory studies of the dc electron beam focusing in the configuration described above. It was demonstrated that a sheet beam of microperveance 6.3 can be focused in the desired configuration with about 85% beam transmission. The achievement of even this level of transmission is extremely critical to injection conditions and mechanical tolerances on the focusing structure. Further effort and the development of an operable tube hinges on further decisions concerning economic suitability of the very complex configuration needed to focus the high perveance electron beam at low powers.

# II. INTRODUCTION

## \. ULTIMATE GOALS OF THE PROGRAM

The ultimate end object desired from this program is a klystron exhibiting he performance specification shown in Table I. Since all previous electrostatically ocused klystrons had used relatively low perveance beams and a cylindrical geometry, ınd since this low perveance is not capable of giving the required bandwidth in normal :lystron operation, some major changes in the state-of-the-art were required. It is ›ossible, of course, to meet the higher bandwidth at a fixed beam voltage through the ıse of extended interaction; however, the requirement for high efficiency operation ›ver a 100 to 1 dynamic range in a single tube rules out completely any possibility of :oupled interaction structures. It was, therefore, determined that electrostatic means nust be determined for focusing a high perveance electron beam. Preliminary es-imates showed that a microperveance of approximately 6 would be required. There s precedent for focusing beams of this perveance or even higher in a hollow configura-ion with center electrodes. However, this leads to the possibility of direct feedback lown the coaxial structure and leads to severe oscillation problems. It was thus lecided that a strip beam configuration would be used. Figure 1 shows the basic con-:ept upon which work was initiated.

## 3. PROGRAM OF RESEARCH AND DEVELOPMENT

A large number of steps of investigation are required before the concept llustrated in Figure 1 can be reduced to practice. The principal steps are the 'ollowing:

(1) Electrical design of beam and focusing system

(2) Electrical design for bandwidth

(3) Electrical design for high efficiency

## TABLE I

## DESIRED PARAMETERS OF ELECTROSTATICALLY FOCUSED KLYSTRON

| | | | |
|---|---|---|---|
| Power Output ($\omega$) | 100 | 20 | 1 |
| Beam Voltage (V) | 1000 | 550 | 227 |
| Beam Current (ma) | 200 | 81 | 22 |
| Overall Efficiency (%) | 50 | 45 | 30 |
| Instantaneous Bandwidth | 10 megacycles between 1 db points | | |
| Large Signal Gain | Minimum of 30 db at all power levels | | |
| Frequency | Center Frequency of 2.295 Gc | | |
| Focusing | Electrostatic | | |
| Reliability | Maximum possible, consistent with space applications | | |
| Life | 50,000 hours, design minimum | | |
| Weight | Shall not exceed 2 pounds | | |
| Cooling | Conduction cooling only | | |
| Temperature | -50°C to +75°C | | |
| Pressure | 760 mm to $10^{-8}$ mm of Hg | | |
| Vibration | 20 g RMS from 24-2000 cps, log sweep | | |
| Acceleration | Shock: 50g for 10 milliseconds<br>Static: 50g | | |

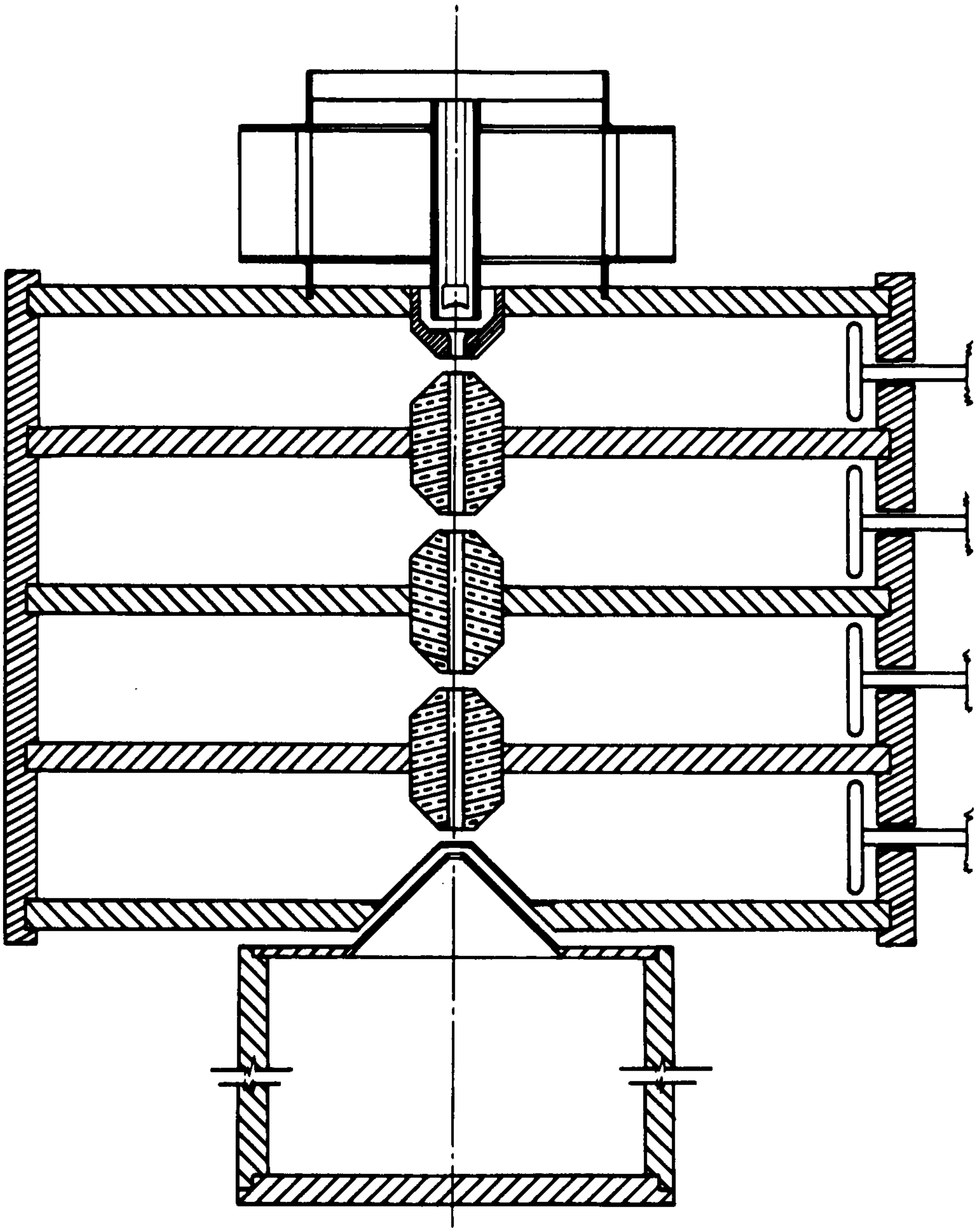


FIGURE 1
DESIGN SKETCH OF EXPERIMENTAL TUBE

(4) Mechanical design of the focusing system

(5) Mechanical design of the rf system

(6) Mechanical and thermal design of the cathode

(7) Experimental verification of the focusing technique, both with and without rf present

(8) Overall design of the tube, including environmental problems

(9) Construction and demonstration of a completed tube type

During the course of this contract, Items 1, 2, 3, 4, and part of 7 were completed. In the following sections these will be described. Section III covers the design considerations for the high efficiency, electrostatically focused klystron. Section IV covers the experimental work which was done during the course of the contract.

# III. KLYSTRON DESIGN CONSIDERATIONS

## A. ELECTRICAL DESIGN

### 1. Basic Approach

The required operating range of 1 watt rf output to 100 watts rf output eliminated the use of voltage sensitive interaction regions, in particular extended interaction circuits. Restricted to single-gap cavities and given the instantaneous bandwidth and gain requirements, the beam microperveance is essentially established and was then chosen to be 6.3.

A solid cylindrical beam of this perveance, with beam to drift tube ratio of 0.7, would suffer a maximum potential depression of 18% in the unmodulated beam. This is a strong argument against such a beam even if it could be well focused. A hollow beam would obviate this problem but requires a center electrode for focusing which greatly enhances the possibilities of oscillation.

A strip beam of the required perveance can be arranged to suffer only a small amount of potential depression by proper choice of beam width to beam thickness and requires no center electrode. It is also important that the defocusing forces can be controlled by choice of beam width to beam thickness, these forces being the same as those involved in the potential depression.

Given this microperveance 6.3 strip beam and single-gap interaction cavities the basic approach is fixed. The focusing period and strength, the drift tube and gap dimensions, the exact number of cavities and their parameters, the gun structure and collector design and the specific details with regard to each are discussed in the following sections.

## 2. Gun and Focusing

The design of the focusing structure must be accomplished subject to restrictions imposed by cathode loading and rf interaction considerations. These restrictions taken in conjunction with available theory provide a guide for an initial design. This design may then be subjected to analysis by digital computer. Study of these results leads to a design modification which, in turn, is analyzed on the computer and the results studied. This procedure is repeated sufficiently to provide a satisfactory final design.

One may describe conceptually a series of lenses just strong enough to re-converge a spreading beam[1], or alternatively, one may study electron motion in a sinusoidally varying electric field[2]. Using the latter approach, the potential in the absence of space charge is approximately given by (see Figure 2):

$$V = V_o(1 + K \sin\nu z \cosh\nu y)$$

where $\frac{2\pi}{\nu}$ is the focusing period and K represents the focusing field strength.

$$K = \frac{V_1}{V_o \cosh\nu a}$$

As shown by Adler, et al., the motion of an electron through this type of field is approximately described by motion in an effective potential $V_e$, given by

$$V_e(y) = -\frac{1}{4} eV_o K^2 \nu^2 y^2$$

The effective restoring field is

$$E_e(y) = -\frac{1}{2} eV_o K^2 \nu^2 y$$

- - - - - - -

1. Pierce, J. R., Theory and Design of Electron Beams, 2nd Edition, Van Nostrand, 1954, p. 145ff.

2. Adler, Kromhout and Clavier, "Resonant Behavior of Electron Beam, in Periodically Focused Tubes for Transverse Signal Fields," Proc. IRE 43, pp. 339-341 (March 1955).

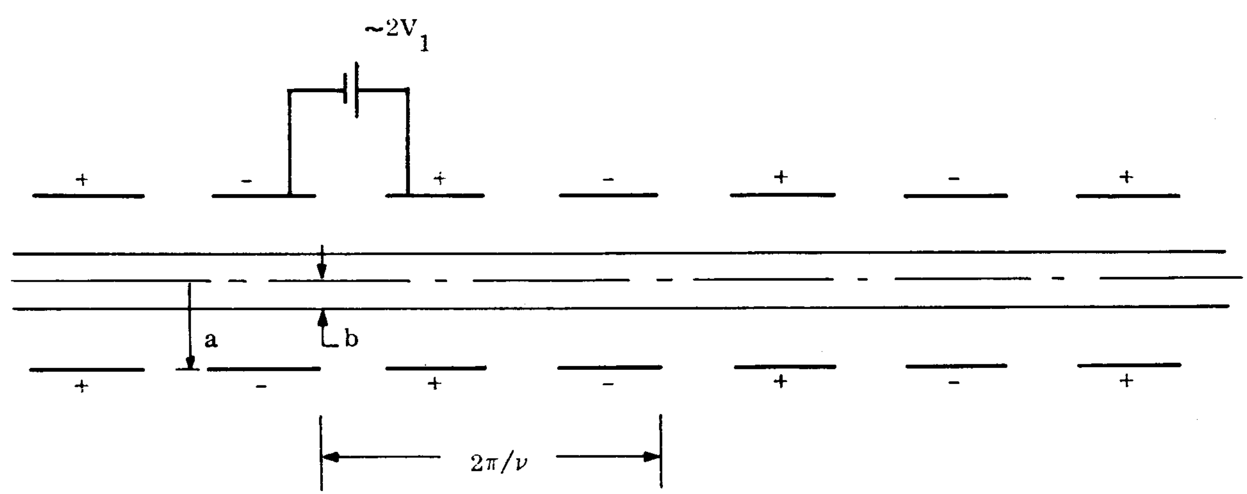



FIGURE 2
SKETCH SHOWING PARAMETERS AND
DIMENSIONS REFERRED TO IN ANALYSIS

If space charge is now included, a uniform beam of density $\rho$ generates a field

$$E_\rho = \frac{\rho}{2\epsilon_o} y$$

If these fields balance, the beam is held in equilibrium at a charge density

$$|\rho| = e\epsilon_o V_o K^2 \nu^2$$

After algebraic manipulation this may be written as

$$\frac{2b}{d} \frac{I}{V_o^{3/2}} = 20.9 \times 10^{-6} \frac{(\nu b)^2}{\cosh^2(\nu a)} \left(\frac{V_1}{V_o}\right)^2$$

This last expression is in the form of perveance per unit square of beam, and is convenient for the calculation of the required $\nu$. It is subject to a number of approximations. The most severe is that transverse motion is small. This condition is violated to some extent, yet the theory did serve its purpose in providing a reasonable initial design. Rearranging this last expression:

$$\frac{\nu^2}{\cosh^2 \nu a} = .603 \times \left(\frac{V_o}{V_1}\right)^2 \times \frac{1}{bd}$$

The drift tube dimension 2a must be chosen in conjunction with gap size to give satisfactory rf beam coupling and is established as 40 mils. This average beam thickness in the interaction region is taken to be 28 mils. The beam enters to the first focusing structure under a positive electrode (a point of minimum beam thickness) and has not yet been subjected to much rf defocusing force. It is chosen to enter with a thickness of 14 mils (b = 7 mils).

Choosing a cathode loading of 1 amp/cm$^2$ and a beam convergence of just under 6, the beam width (d) is found to be 400 mils. Only $V_o/V_1$ remains to be chosen in order to establish the $\nu$, the focusing period. Choosing $V_o/V_1$ equal to unity:

$$\frac{\nu}{\cosh 20\nu} = .0147 \qquad \text{and} \qquad \nu = 0.15$$

The focusing period $\frac{2\pi}{\nu}$ = 42 mils. The focusing period arrived at in the final design was 60 mils.

The parameters established above were used for the initial design and the iterative design procedure described above was begun. After several iterations from which a satisfactorily converging solution was emerging, the program was extended to simulate the transverse defocusing forced caused by bunching.

Since the basic computer program is inherently time independent, it is impossible to actually simulate the time varying component of beam current. The transverse defocusing forces due to bunching may be approximated, however, by increasing the charge density as a function of longitudinal position. A bunch length of $\frac{2\pi}{3}$ will exhibit transverse forces approximately three times as great as the unbunched beam. Taking a 120° bunch as an acceptable degree of bunching, the charge density was increased linearly with longitudinal position at a rate which would triple the density at the third gap. The actual tube would have seven gaps and the increase in defocusing forces would be more gentle. The three gaps were chosen for computer analysis in the interest of economy.

The final design is shown in Figures 3A through 3H with trajectories and equipotentials. In these figures the gun microperveance is 6.3 and has been increased linearly to 18.0 over the distance between the center of Gap 1 and the center of Gap 3. The collector region analysis was accomplished simultaneously with the last few focus structure analyses and the results patched on as Figure 3H. Thus there is a slight discontinuity shown in the region of the third gap which was not felt to be of sufficient consequence to warrant the required expenditure of computer time needed to correct it.

This final design of the focusing structure is the model used for all hardware design and experimental work. Note that the principle behind the use of hard

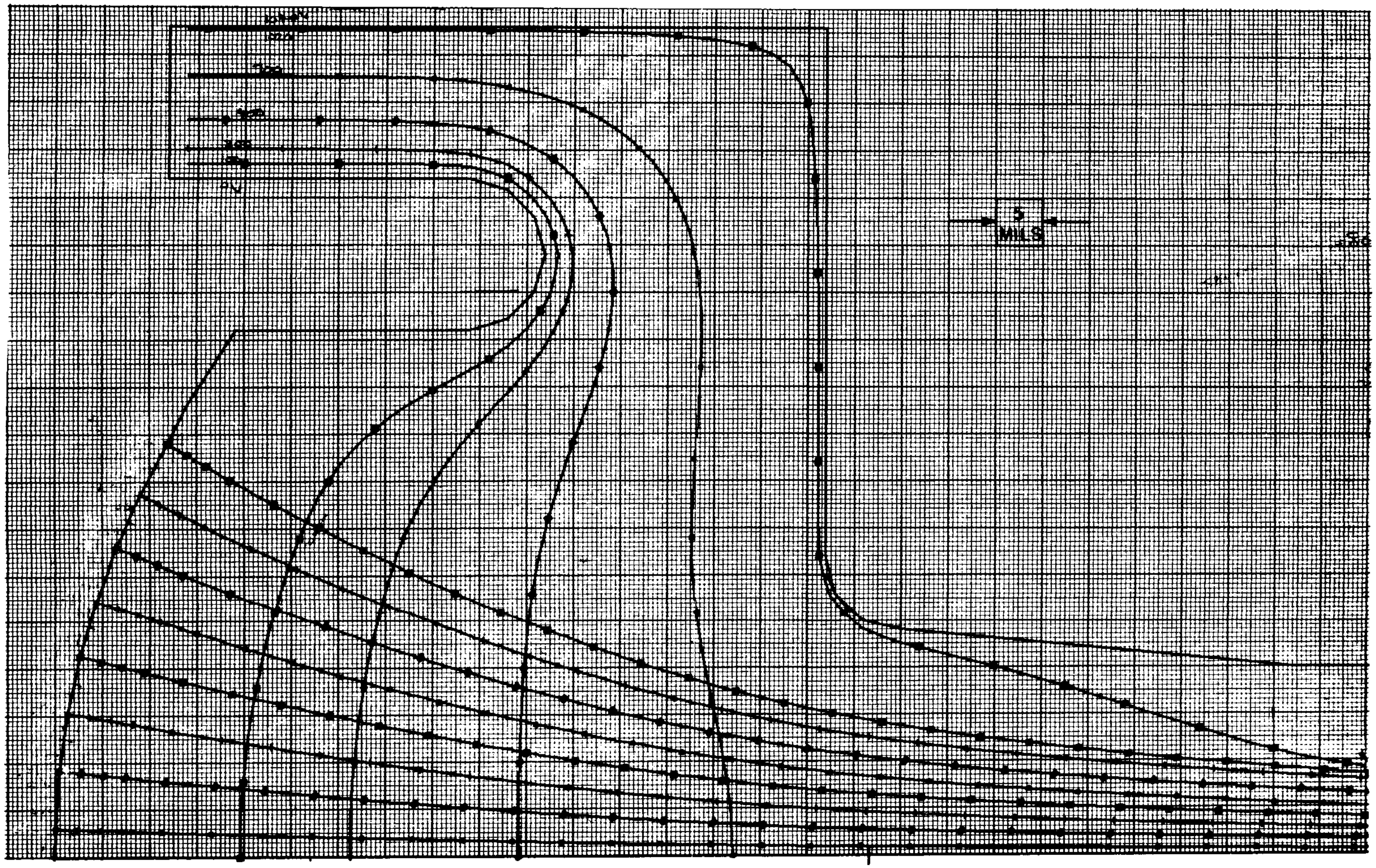



FIGURE 3A
FINAL DESIGN OF GUN AND FOCUSING
STRUCTURE FOR HIGH PERVEANCE STRIP BEAM

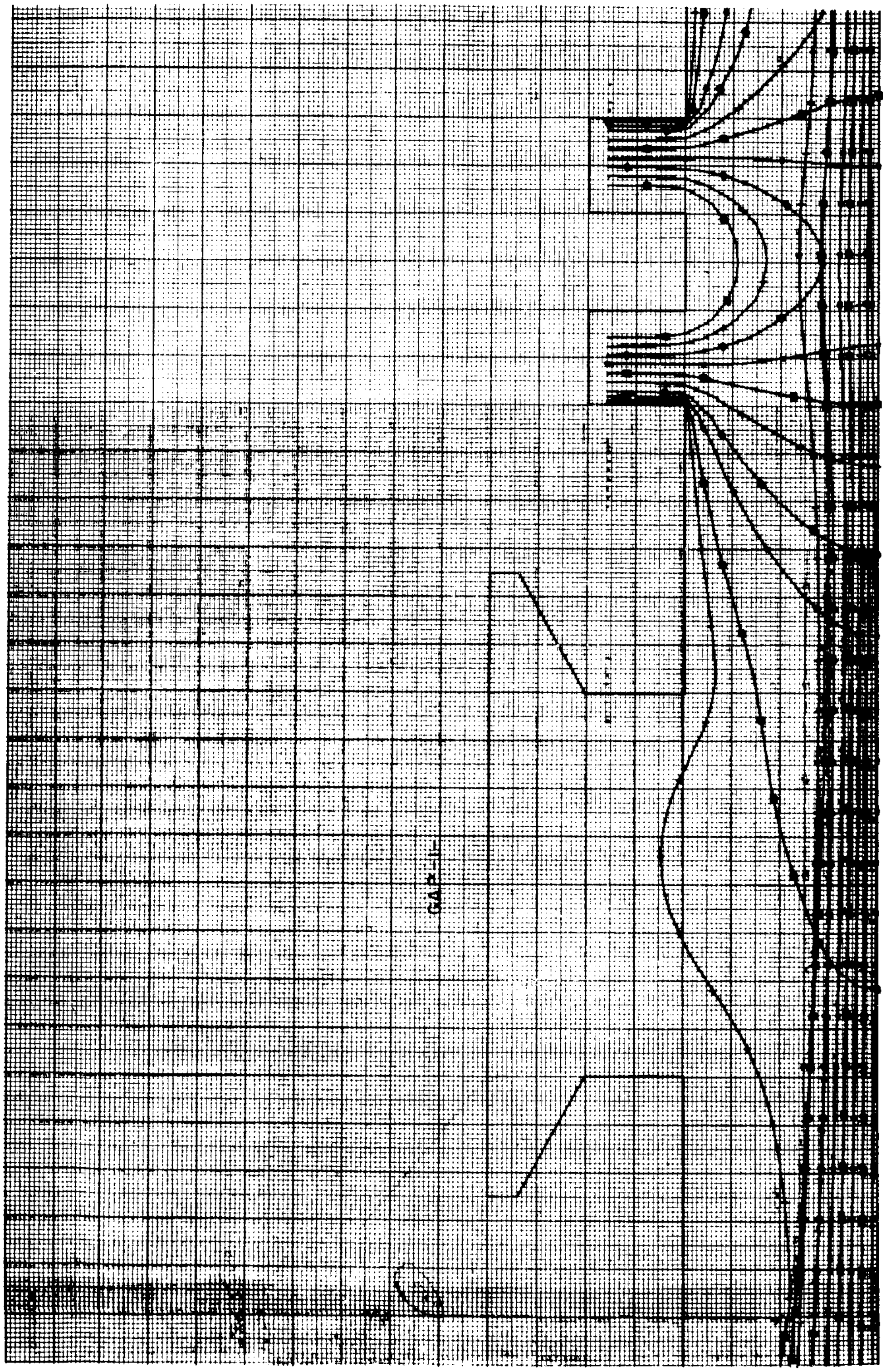



FIGURE 3B

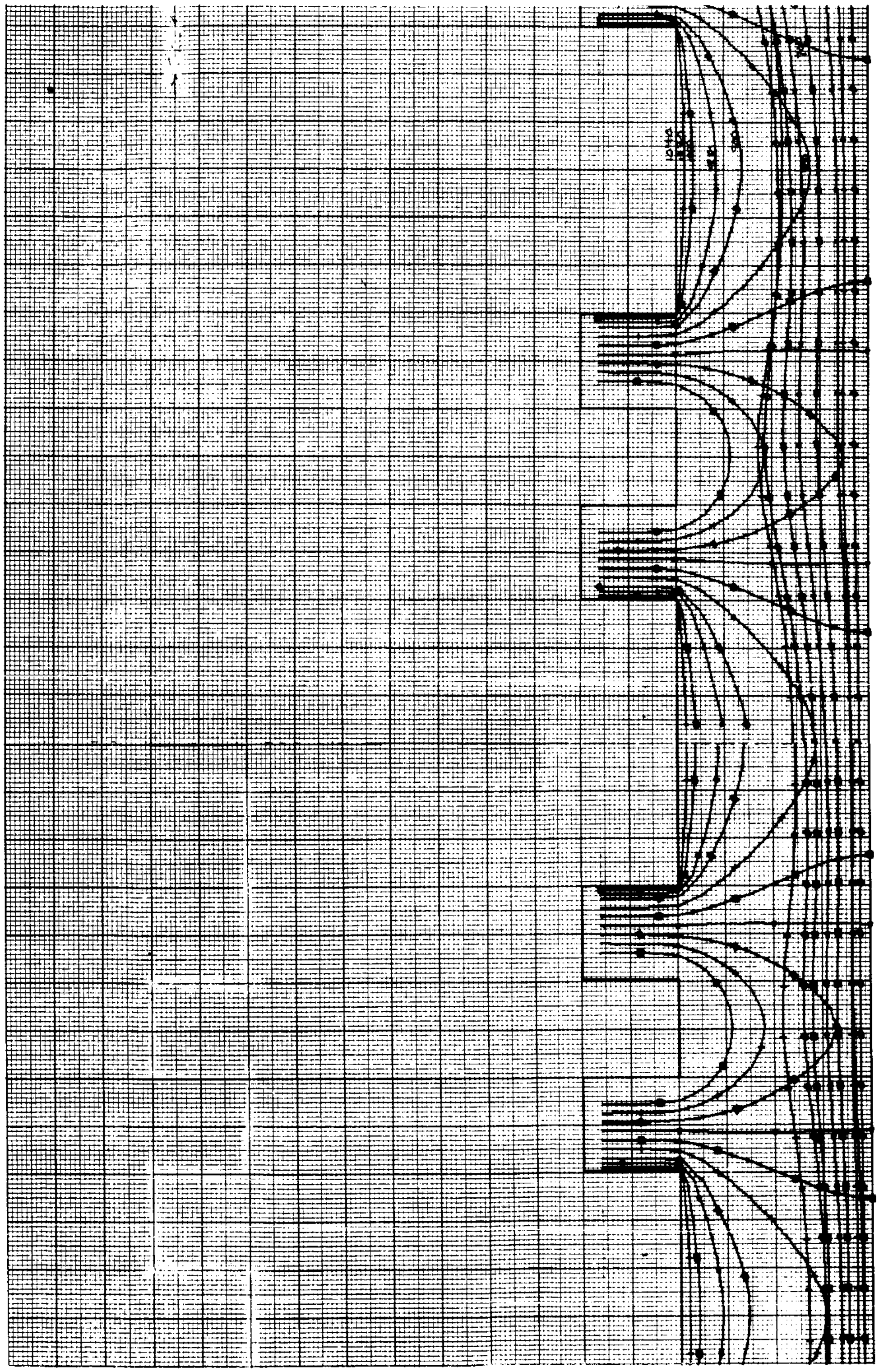


FIGURE 3C

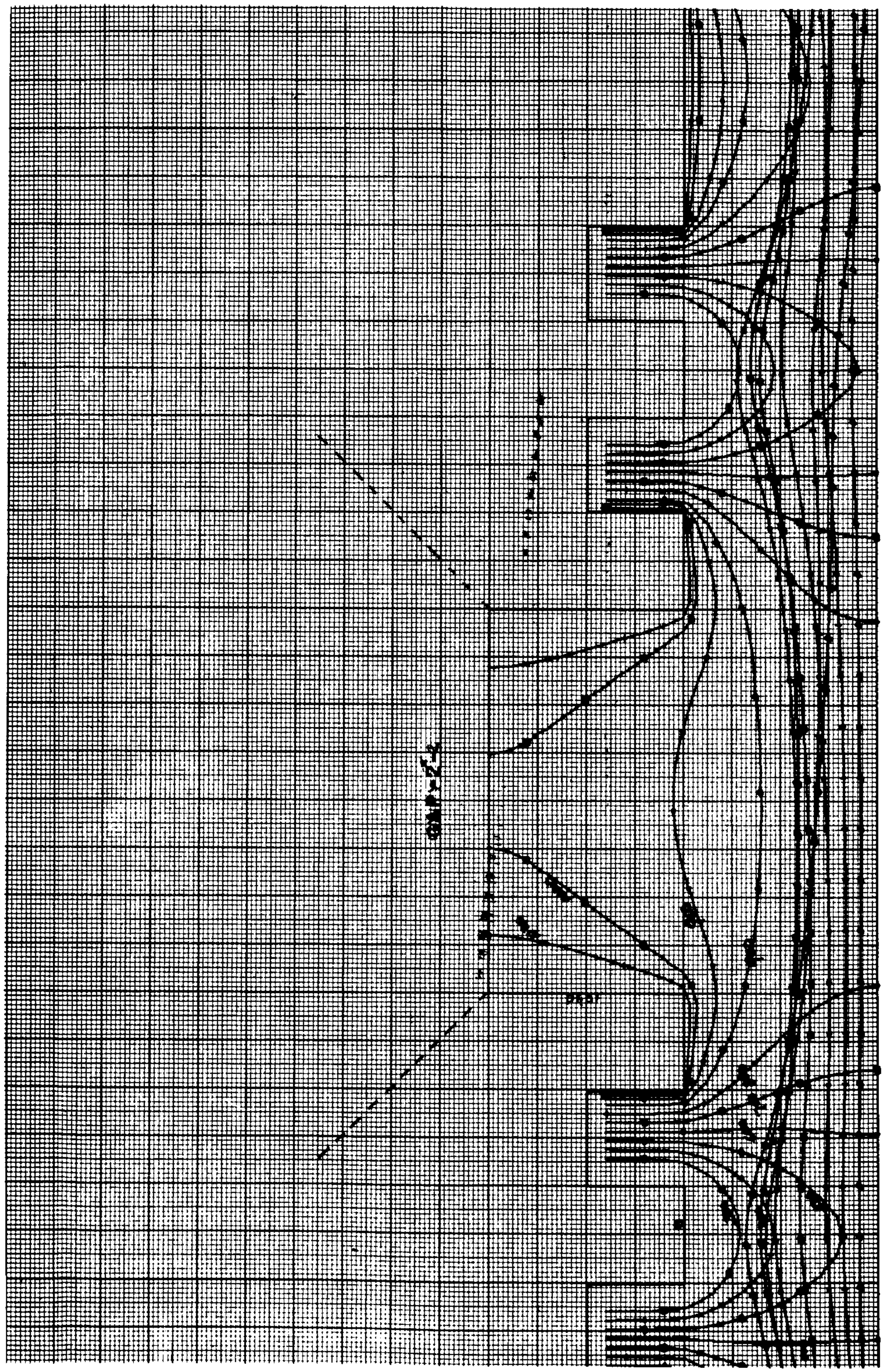


FIGURE 3D

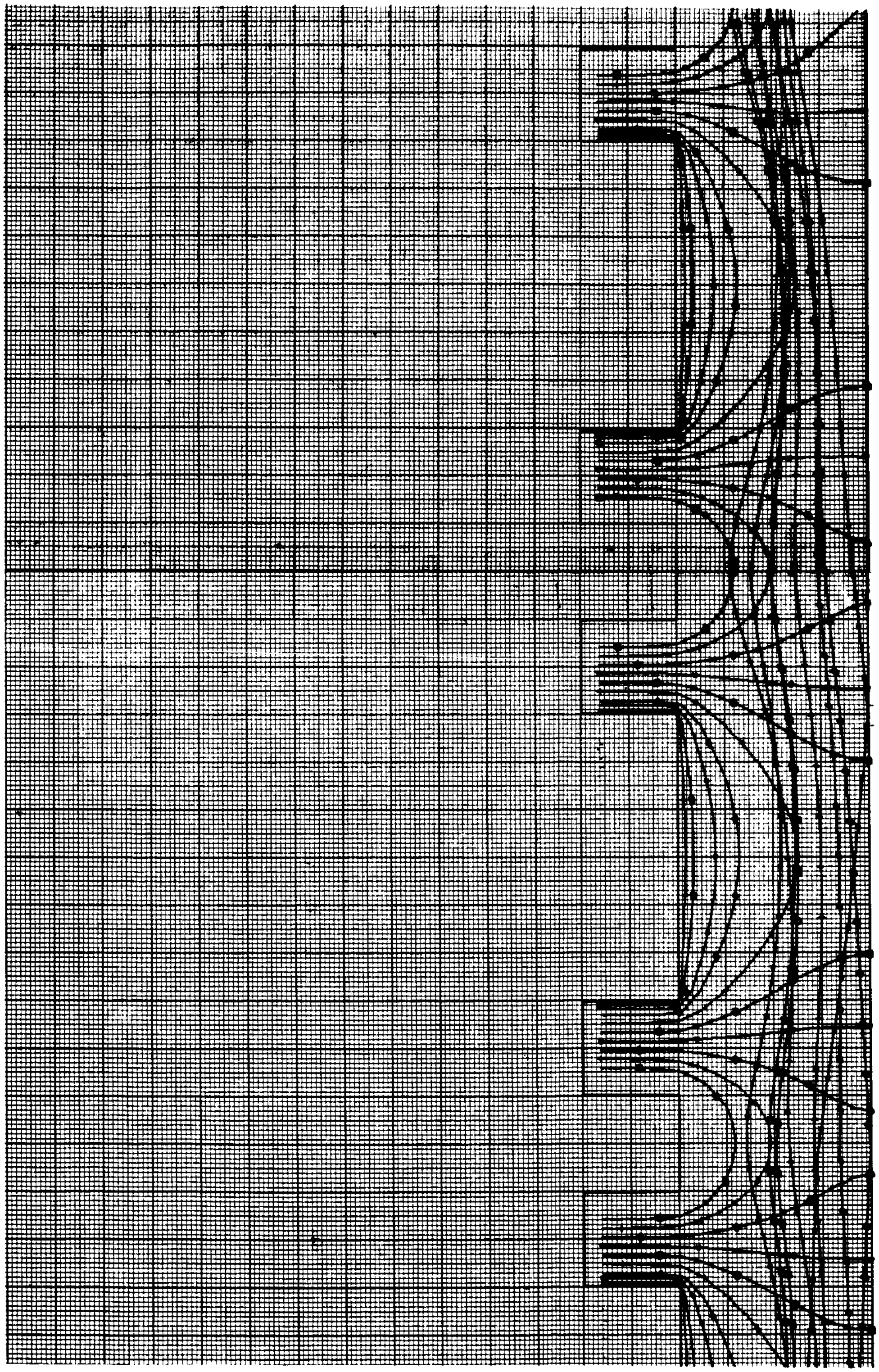


FIGURE 3E

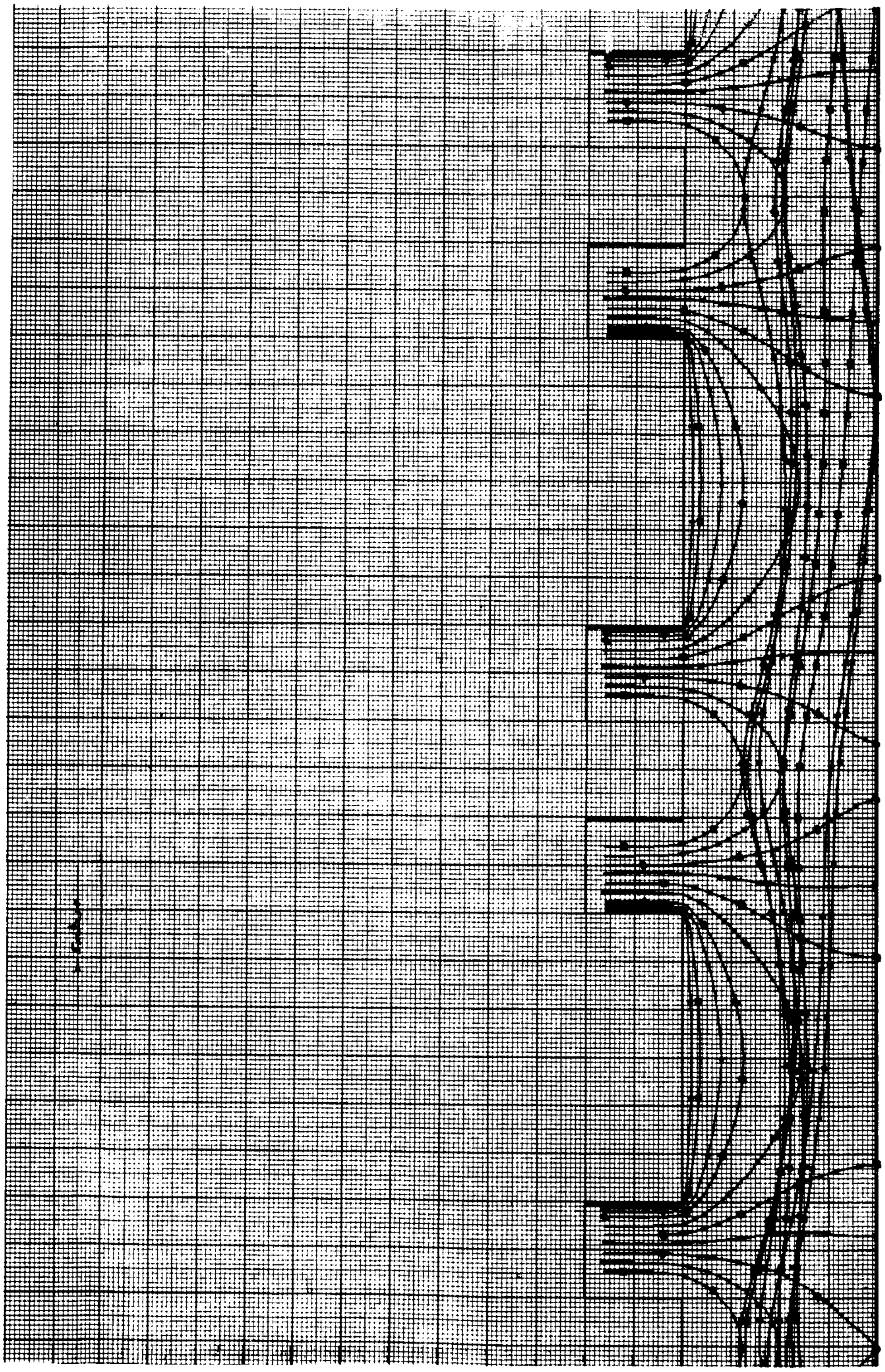


FIGURE 3F

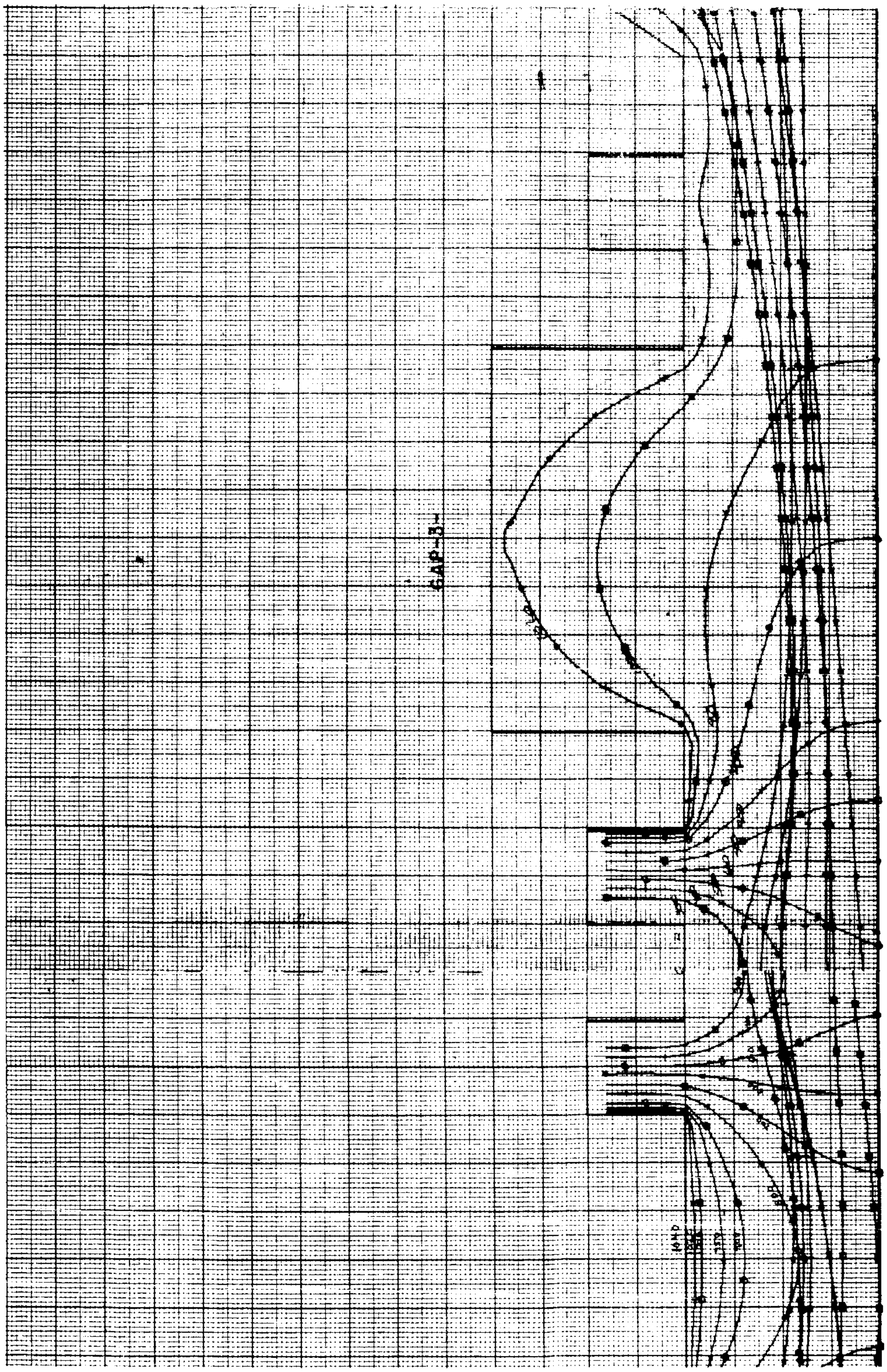



FIGURE 3G

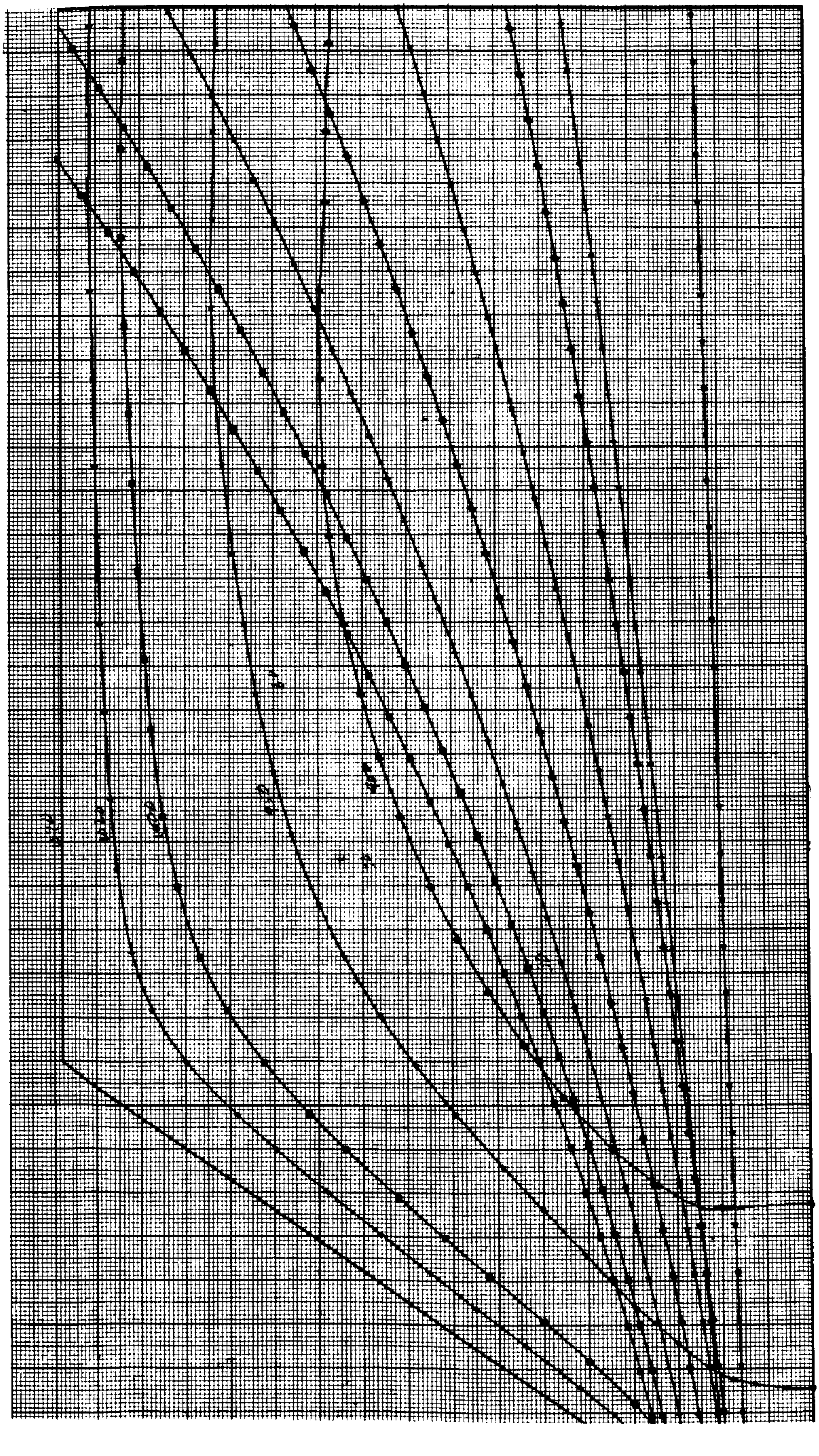


FIGURE 3H

focusing, viz, space-charge forces much less than focusing field forces, seems to be valid. A tripling of space-charge forces causes a spreading of the beam but leaves it still under control.

A second valuable feature of hard focusing is the absence of dc slippage across the beam. In order that the rf bunches hold together, all electrons must have essentially the same dc velocity. If this were not the case, there would exist a strain on the rf phase focusing mechanism which would degrade the efficiency to an extent dependent on the amount of slip. A computer study was made of dc slippage in the beam. The maximum slip per gap-to-gap distance was computed to be only 2% of the gap-to-gap transit time. This study of slippage concluded the computer design work on the gun and focusing system.

Since the entire study was made in two dimensions, the problem of edge effects remains. One can make the qualitative argument that closing the focus electrodes around the edges should provide sufficient focusing field strength in this region. The periodicity remains unchanged and the space-charge forces are highly inferior to the focus field forces. The extreme complexity of a three-dimensional analysis leads one to accept the qualitative argument and to experimentally measure the edge interception, if any, in lieu of seriously attempting this analysis. As reported later in this report, beam interception on the edge electrodes was in fact negligible.

### 3. Efficiency

The efficiency requirements over the large range of output powers presents a considerable problem. The efficiency is of course highly dependent on the load presented to the beam across the output cavity gap. Experience has shown that for best efficiency this load should be approximately 1.4 x dc beam impedance. The output cavity load coupling structure is fixed but the dc beam impedance varies with beam power. Two schemes were taken into consideration.

The first was the ideal approach, that of synthesis of the desired beam bunch configuration through what may be called adiabatic bunching. Fundamentally, adiabatic bunching consists of a large number (7 to 10) of closely spaced, inductively tuned cavities directly preceding the output cavity. In this fashion, an attempt is made to form ever-tightening bunches without introducing velocity spread and thus keeping the inter-bunch region relatively free of electrons. Unfortunately, this turned out to have no practical value in this particular application. The theory of adiabatic bunching as it has been derived at Varian Associates over the past year shows that the large signal or high efficiency bandwidth of this technique is directly related to beam voltage but not to beam perveance. The operating voltages under consideration were too low, particularly at the lower power levels, to admit of a bandwidth of 10 Mc. The small signal driver section required high perveance to achieve the 10 Mc bandwidth and as a result, it was not possible to go to higher voltages and the adiabatic bunching was dropped from consideration.

The second scheme considered for efficiency involves variable collector depression. It is well known that for high efficiency operation, the load presented across the output gap must be such that the driving current in the beam can generate an rf voltage across the gap sufficient to stop a $V_o$ electron. Given that a load coupling structure is designed to do this at the 100-watt level, it will not also accomplish this end at lower power levels. Therefore to achieve high efficiency at these lower levels, the collector must be depressed. It is also reasonable and borne out by experience that as the output gap voltage continues to decrease below $V_o$, the collector can be depressed more and more without creating serious problems from returned secondaries. In this fashion the efficiency can be maintained with decreasing power level. Representative depressions would be 5% at 100 watts, 28% at 20 watts and 54% at one watt. One simply keeps constant the ratio of collector voltage to beam current and starts with 5% as a relatively safe way of picking up a few per cent at the start.

While the above scheme is meant to keep the efficiency relatively constant with power, an effort must be made to insure that this constant value is sufficiently high. The most effective design tool for high efficiency in a klystron is simply the great wealth of experimental evidence on hand. It is known that single-gap efficiency increases as:

(1) Drift tube hole is decreased (dimension a of Figure 2),

(2) Output gap is shortened (limited by multipactor and voltage breakdown),

(3) Beam filling factor is increased (ratio of b/a in Figure 2),

(4) Potential depression is decreased.

These parameters must be chosen with the large operating range in mind and are shown in Table II for three power levels along with the other appropriate parameter values.

The value of $\gamma a$ of 0.39 radian at the 100-watt level causes the entire focus structure to be quite small and presents mechanical design problems. It is forced however, not only by efficiency considerations at the 100-watt level but most decidedly by efficiency considerations at the one-watt level where $\gamma a$ is up to 0.92 radian and hints at some difficulty in meeting the efficiency requirements at this level.

4. Bandwidth

The bandwidth requirement of 10 Mc must be met by the driver section and by the output section at 100 watts and one watt and all intermediate levels. This bandwidth at the one-watt level is a difficult specification for high efficiency operation, but the most severe problem consists in providing 10 Mc at all levels with the same driver cavity tunings and the same load across the output gap. It is the bandwidth specification that requires the high perveance.

The output circuit is designed to present the proper load to the beam at the 100-watt level. The ensuing loss of efficiency at lower level operation is compensated for with a variably depressed collector as presented in the previous section. This arrangement makes the output circuit design straightforward.

The load resistance ($R_L$) to be presented across the output gap is:

$$R_L = 1.4 \frac{V_o}{I_o} = 7000\Omega$$

The R/Q of the driver cavities was measured and found to be 44Ω. Since the beam need not be focused beyond the output gap, the output cavity can be different from the driver cavities and a higher R/Q achieved. In the interest of having a safety factor where possible, an R/Q of 44Ω will be used in the paper design of the output cavity. For a single-gap, single-tuned cavity the bandwidth is given approximately by:

$$\Delta_r = \frac{1}{Q_o} \sqrt{\frac{1}{r} - 1} \qquad \text{where} \qquad Q_o = \frac{R_L}{\frac{R}{Q}}$$

r = rth power point

In the case under consideration $Q_o = \dfrac{7000}{44} = 159$ and $r = 0.8$

$$\Delta_r = \frac{.5}{159} = .00314 \qquad \text{or} \qquad 7.3 \text{ Mc}$$

For a single-gap, double-tuned cavity, the bandwidth is given approximately by:

$$\Delta_r = \frac{2}{Q_o} \sqrt{1 - r^2} = .0075 \qquad \text{or} \qquad 17 \text{ Mc}$$

The driver section presents the problem of maintaining a given response over a voltage range of 5 to 1 with a single stagger pattern. The difficulty lies in the fact that a multi-cavity driver section has zeroes in its gain expression as well as poles. The poles are simply the resonant frequencies of the cavities and are independent of voltage and voltage-dependent parameters. The zeroes however, are dependent on such parameters as reduced plasma frequency, beam conductance, coupling coefficient, etc. Normally one can arrange the poles of the gain function to counteract the effect of any zeroes in the band. In this case, the zeroes will move around while the poles are fixed. It is imperative in this case to keep the zeroes far enough outside of the band so that their movements will not seriously affect the response.

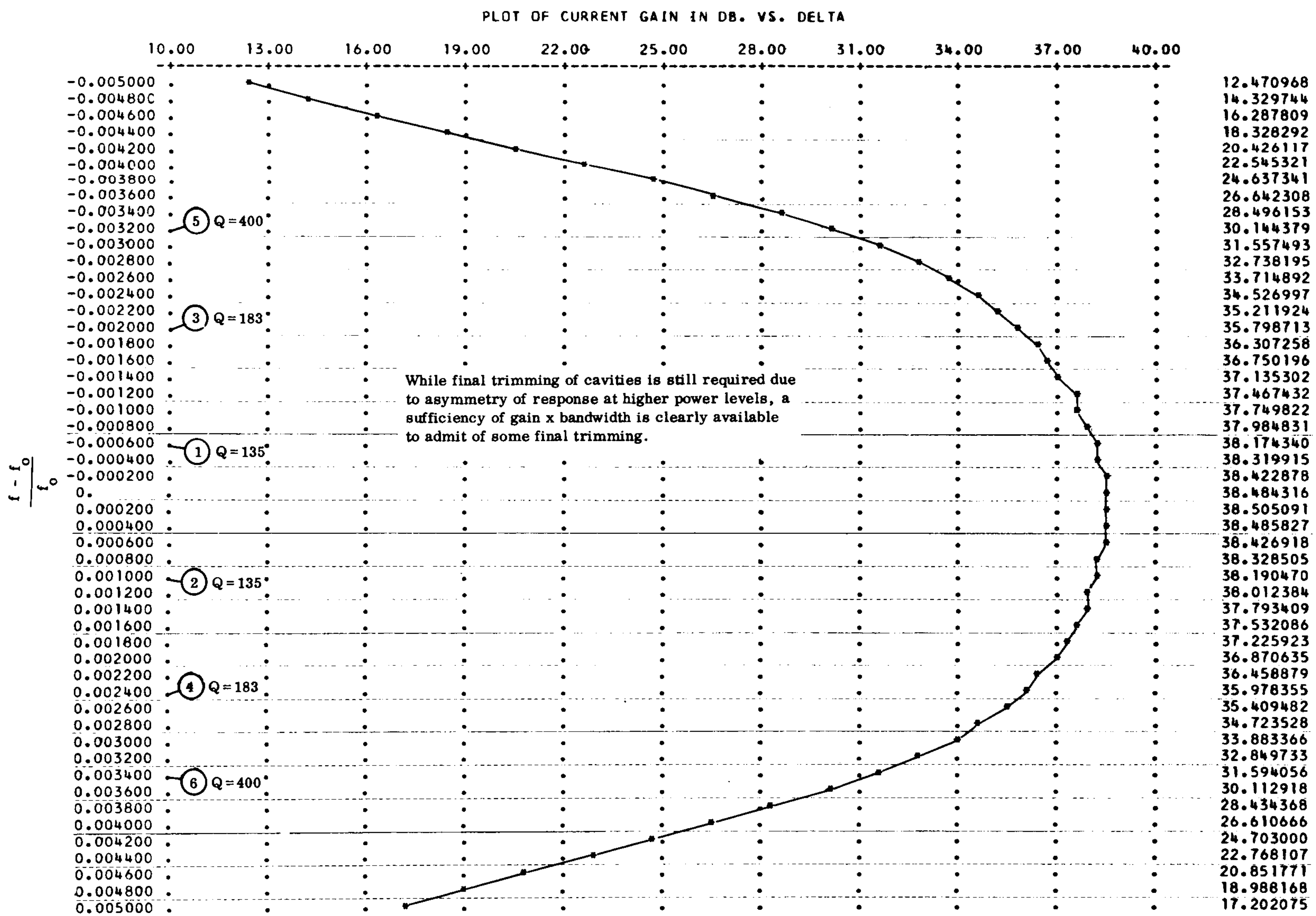
By restricting the tube to a maximum of seven cavities for reasons of weight, complexity and cost, it can be shown that synchronous tuning of the tube will not provide sufficient gain-bandwidth product, irrespective of the extent of external loading of all cavities. This would have been the easiest way to solve the problem of zero shifting.

The solution then will include the use of a stagger pattern and external loading of the driver cavities. This external loading helps to keep the zeroes above the band and also smoothes the phase response.

The cavity $Q_T$'s and the stagger pattern are shown with the accompanying response on Figures 4 through 6, for power outputs of 1 watt, 20 watts, and 100 watts.

5. Tube Design Parameters

Given the operating frequency, power level range, efficiency requirements and bandwidth specification, the first parameter to be chosen is beam perveance. In view of the variably depressed collector operation, the output circuit presents less of a bandwidth problem than the driver section. Since the effect of perveance on gain bandwidth product is known, one can scale from existing tubes. This leads to a design microperveance of about 6.0. Subsequent design work lead to a final choice of 6.3. Efficiency considerations then dictated the drift tube size and dimension 2a (Figure 2) was chosen as 40 mils. Considerations of cathode loading and beam convergence established the beam width of 400 mils. Gap size was chosen for high coupling coefficient for efficiency and gain-bandwidth product (Figures 7 and 8). The curves are derived from an approximate treatment neglecting transverse motion. Gap-to-gap distance was chosen to be 90 plasma degrees for one watt operation.




# FIGURE 4
## SMALL SIGNAL GAIN-BANDWIDTH CURVE FOR POWER OUTPUT OF 1 WATT

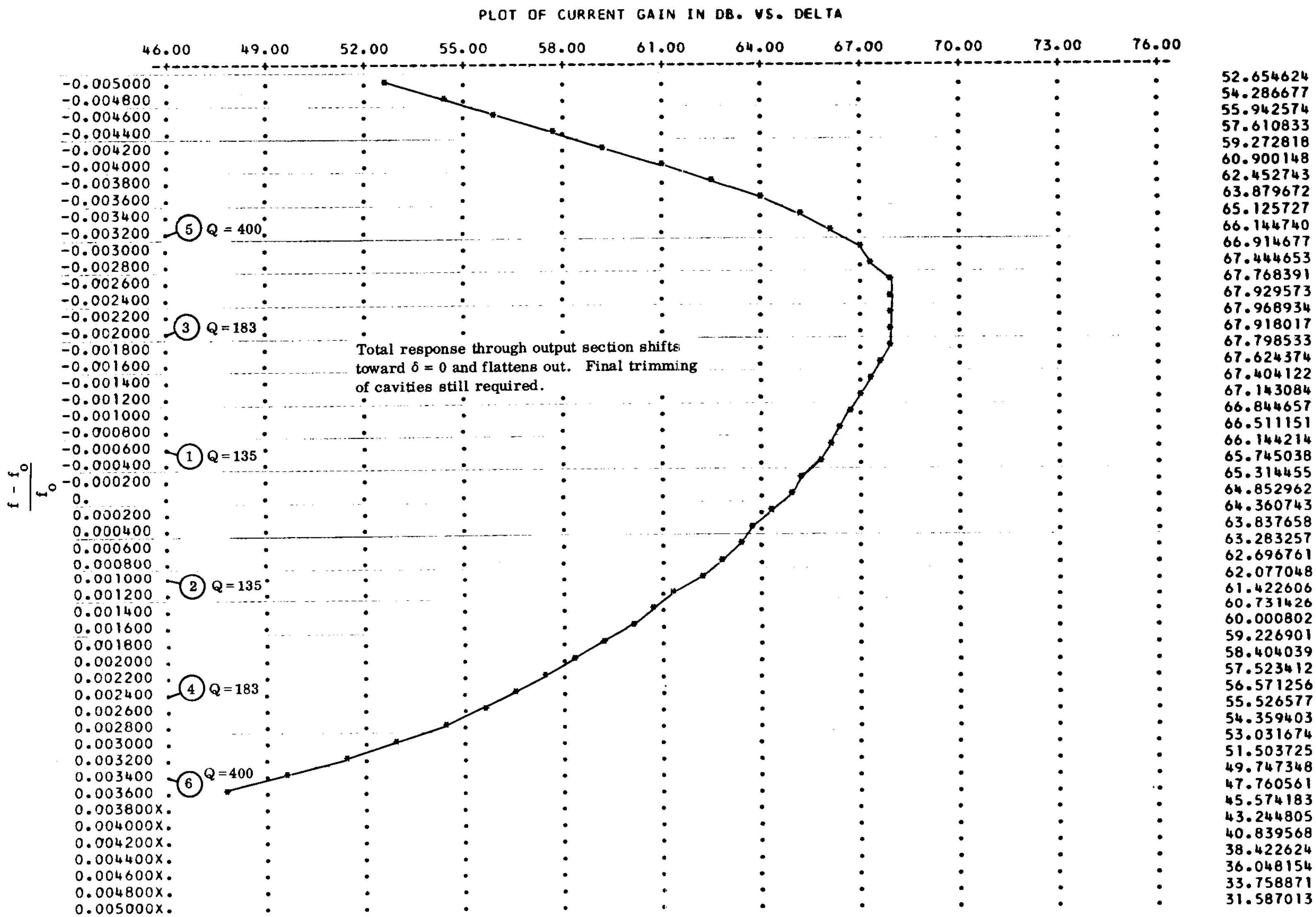
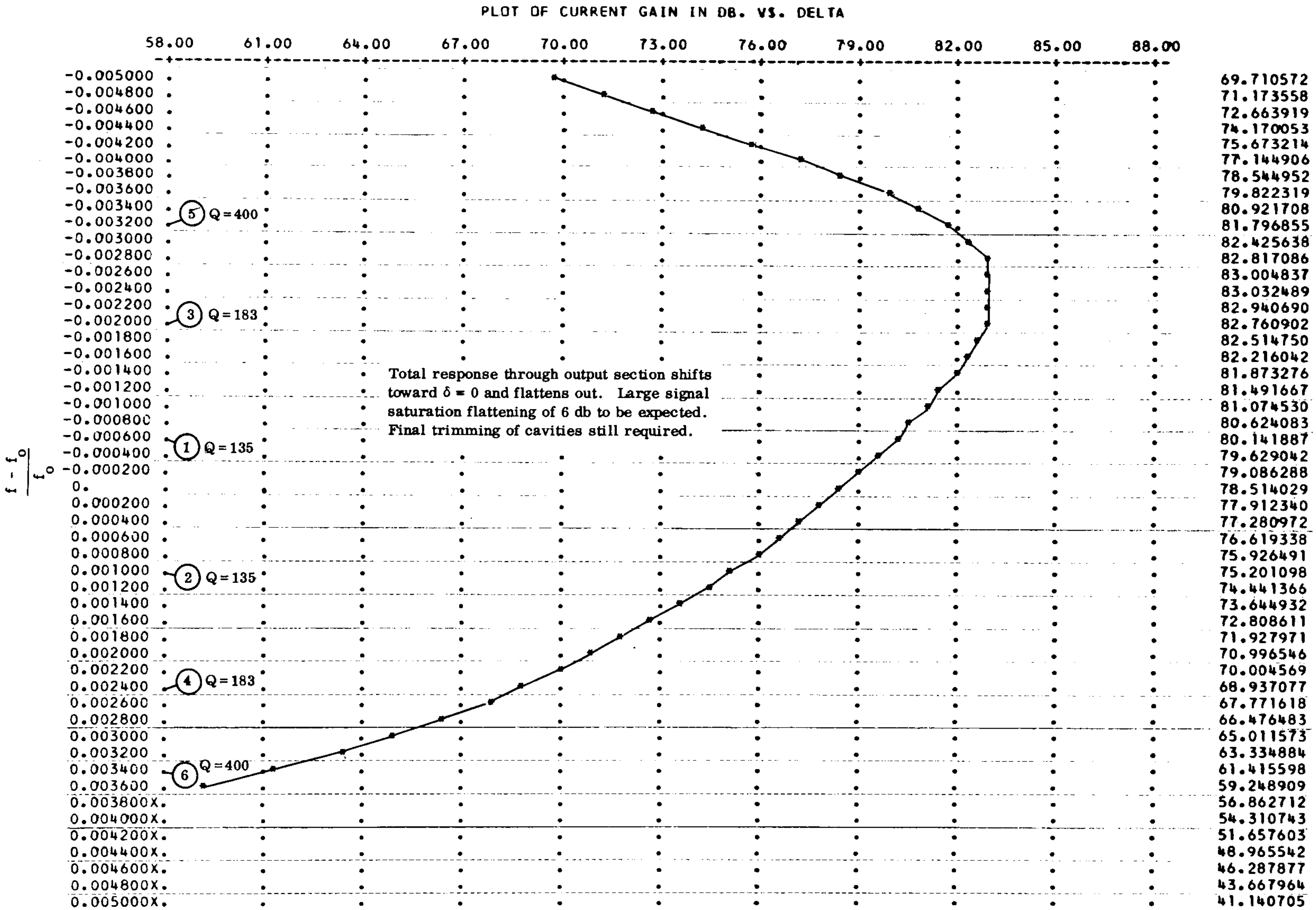



FIGURE 5
SMALL SIGNAL GAIN-BANDWIDTH CURVE
FOR POWER OUTPUT OF 20 WATTS




# FIGURE 6
SMALL SIGNAL GAIN-BANDWIDTH CURVE
FOR POWER OUTPUT OF 100 WATTS

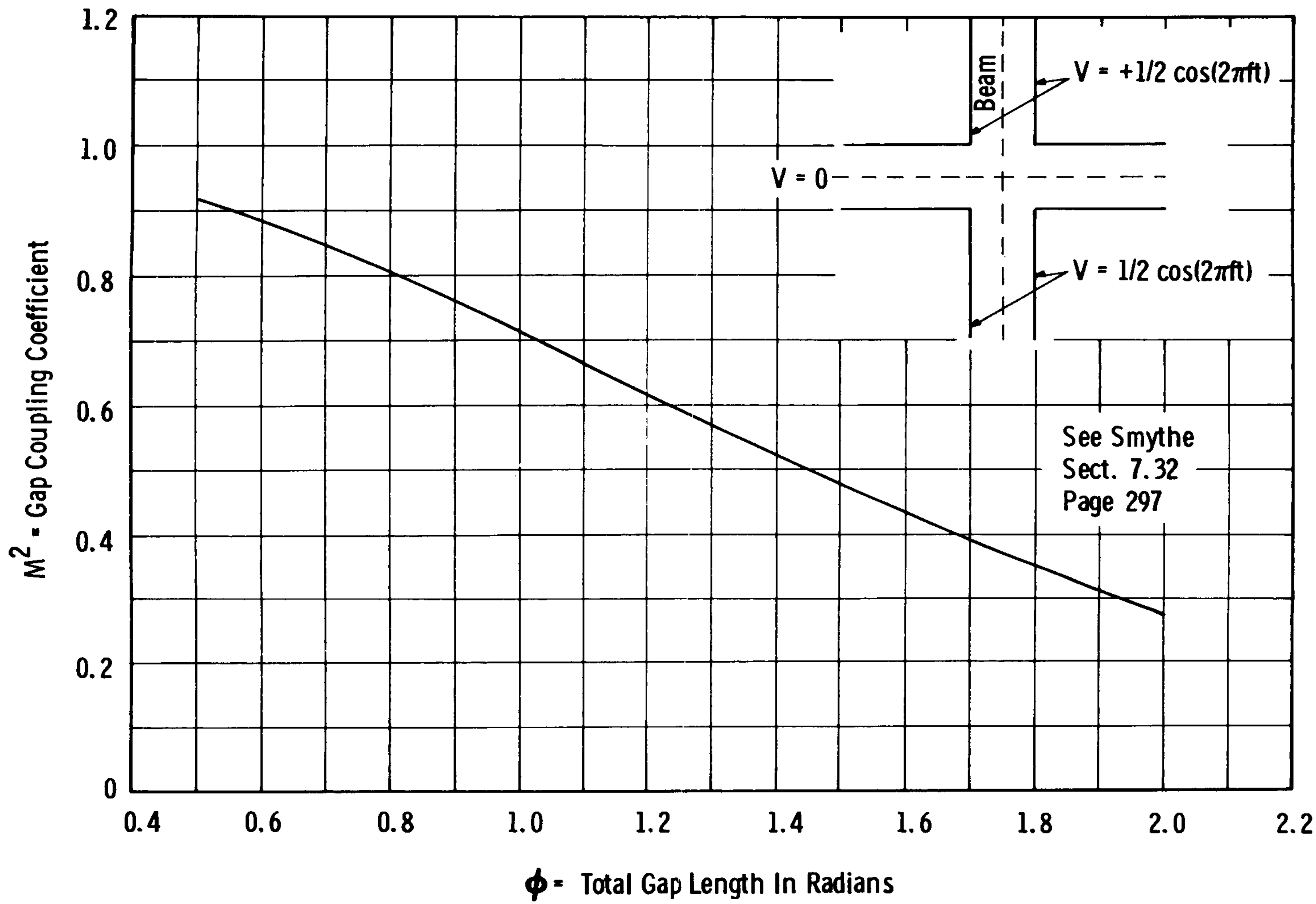



FIGURE 7
GAP COUPLING COEFFICIENT VS GAP LENGTH

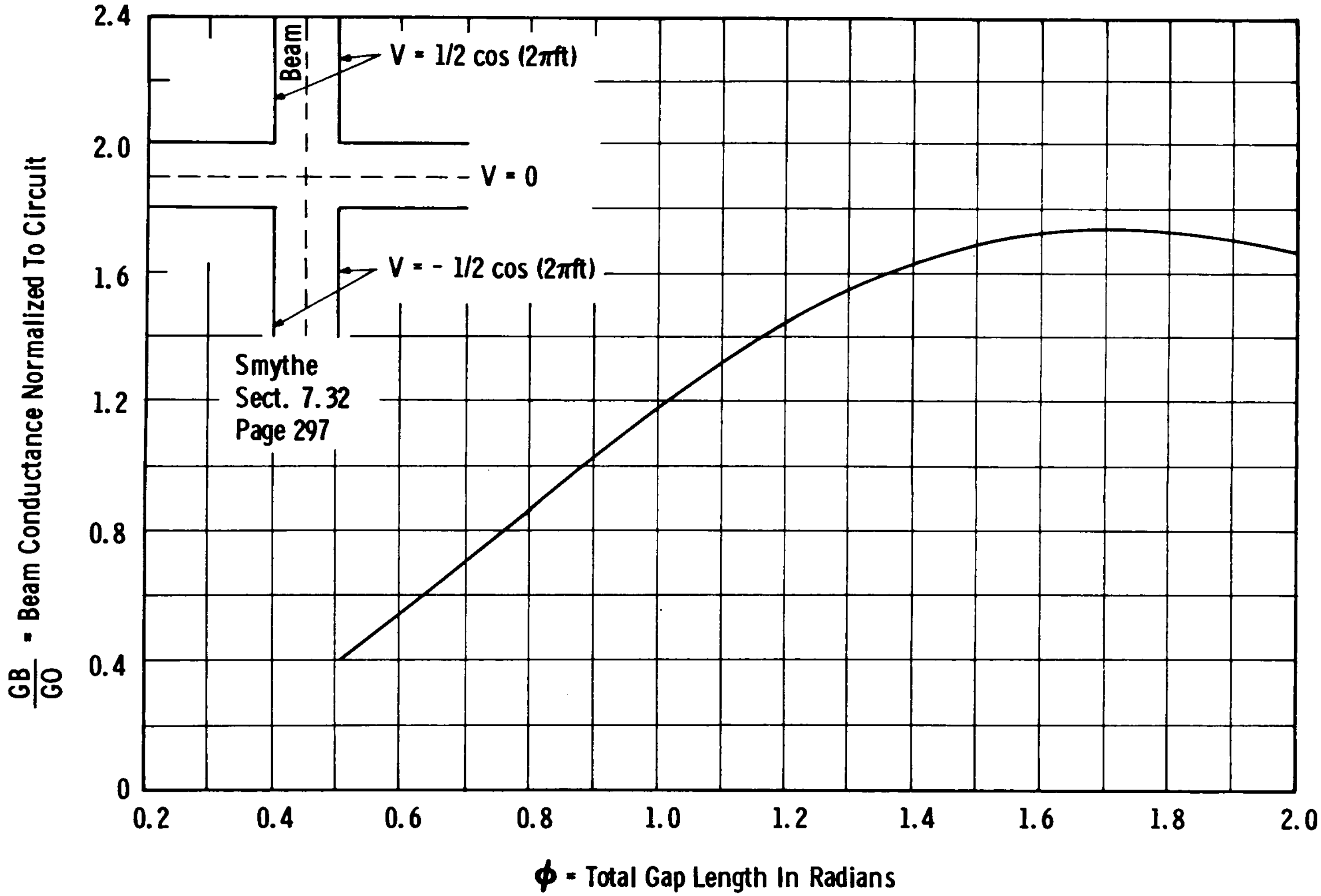



FIGURE 8
NORMALIZED BEAM CONDUCTANCE VS GAP LENGTH

These parameters and other relevant parameters derived from them are shown in Table II.

TABLE II

ELECTRICAL PARAMETERS

| | | | | |
|---|---|---|---|---|
| Output Power | $\rho$ (watts) | 100 | 20 | 1 |
| Frequency | f (Gc) | 2.295 | 2.295 | 2.295 |
| Beam Voltage | $V_o$ (volts) | 1000 | 550 | 227 |
| Beam Current | $I_o$ (ma) | 200 | 81 | 21.6 |
| Drift Tube | $2\gamma a$ (radian) | 0.78 | 1.05 | 1.64 |
| Gap Size | $\gamma g$ (radian) | 0.78 | 1.05 | 1.64 |
| Coupling Coefficient | $M^2$ | 0.81 | 0.69 | 0.415 |
| Beam Loading | $G_B/G_o$ | 0.084 | 0.125 | 0.173 |
| Cavity R/Q (All cavities) | R/Q (ohms) | 44 | 44 | 44 |
| Reduced Plasma Frequency | $F_q$ (Gc) | 0.210 | 0.208 | 0.196 |
| Drift Lengths | $\beta_q \ell$ (radian) | 46° | 61° | 90° |
| Cathode Loading | $J_K$ (A/cm$^2$) | 0.855 | 0.346 | 0.092 |

## B. MECHANICAL DESIGN

### 1. Overall Considerations

The general design problems from a mechanical standpoint consisted in mutually insulating the large number of positive and negative electrodes, maintaining tolerances of less than one mil due to the very small size of the focus structure and designing the entire tube to meet the weight, vibration and acceleration specifications.

The tube was to be of a stainless steel and ceramic construction. The cavities were to be low Q for electrical reasons thus permitting the use of unplated stainless steel. A non-magnetic variety would be used and its strength would be needed to meet the environmental specifications. Where ceramics were to be brazed to metal, monel or even copper would be considered as a buffer material to permit the high temperature brazes without cracking the ceramics.

The initial test vehicle was designed with more copper parts than would be permissible in a specification tube for ease of machining and brazing. The drift tube focus structure was entirely of copper except for ceramic insulators.

### 2. Drift Tube-Focus Structure

Several design rules existed for this structure:

(1) Seven negative focus electrodes per drift tube,

(2) Size of and spacing between electrodes of the order of 10 mils,

(3) Essentially rectangular shape as seen by the beam,

(4) Structure entirely self contained within each drift tube,

(5) All spacings between positive and negative support structures to hold off 1000 volts,

(6) Rf leakage at a minimum, and

(7) Final structure with high strength materials to meet the environmental specifications.

Consideration of the above requirements led to a design characterized as an interdigital vane structure. The negative focus electrodes were to be brazed to a ceramic slab which was in turn brazed to one wall of the drift tube. The focus lead was to be brought out through a hole in the cavity plate (see Figures 9 through 11).

Since edge effects were not amenable to analysis, separately insulated edge electrodes were incorporated in the developmental drift tubes. They replaced only the positive focus electrodes on the edges since the negative focus electrodes were to be held at cathode potential and hence not suffer current interception.

The assembly procedure was:

(1) Braze the metallized ceramic to drift tube side and braze in plug for negative focus electrode lead.
(2) Braze negative focus electrodes to the ceramic.
(3) Braze positive focus electrodes to second drift tube side.
(4) Simultaneously braze edge electrodes to the drift tube ends and the ends to the positive drift tube side.
(5) Braze the negative focus electrode drift tube side onto the positive electrode assembly from step 4.
(6) Braze drift tube into the cavity plate.

The positive and negative focus electrodes required only two simple comb-like structures and a base plate as jigging during the braze. The edge electrodes however created the need for very complex jigging and also required that the drift tube consist of four sides rather than two channel shaped sides.

After evaluation of edge electrodes in the first test vehicle, it is expected that they will not be necessary on future structures. Should it occur that best performance occurs with an edge electrode potential different from body potential, then a redesign of the focus electrodes at the edge can be accomplished to present the same potential to the beam edge as the separate edge electrode. In either case, the separate edge electrode will be eliminated.

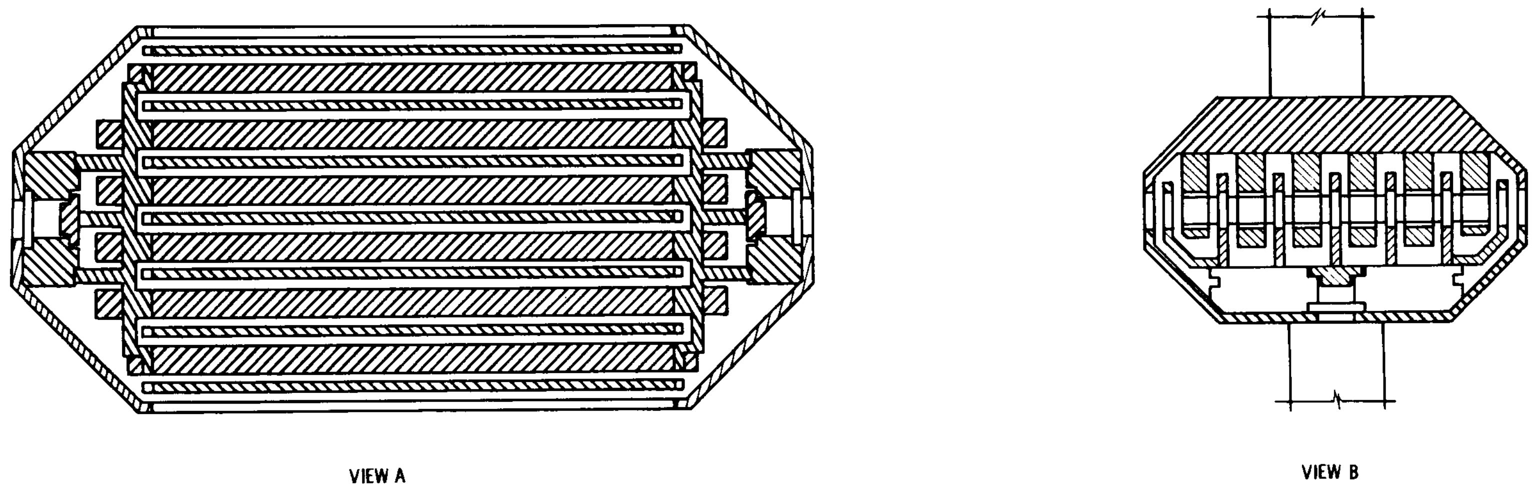



FIGURE 9
CROSS SECTION OF DRIFT TUBE-FOCUS STRUCTURE

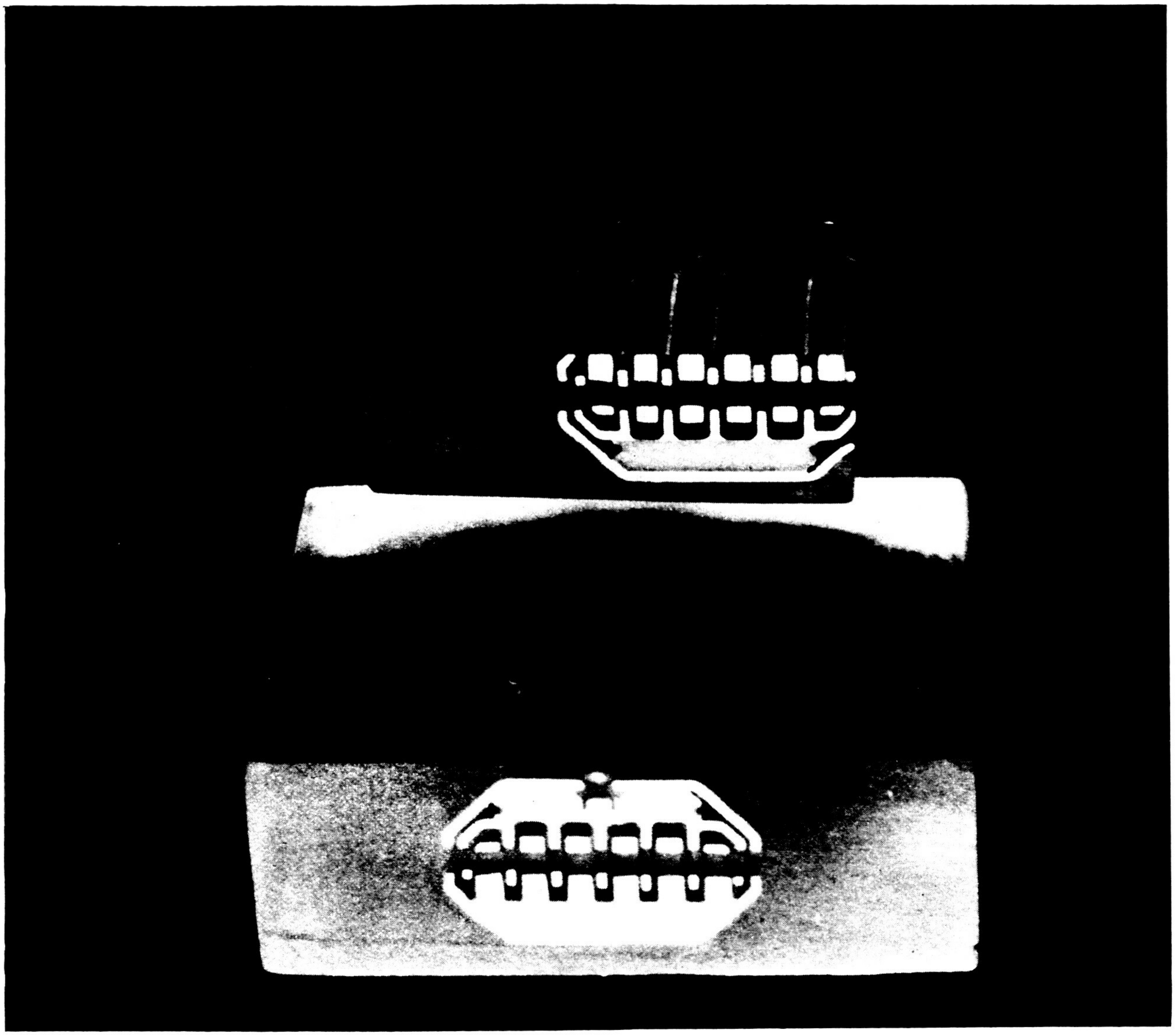


FIGURE 10
CUTAWAY OF ENCAPSULATED DRIFT TUBE-FOCUS STRUCTURE
(LOWER PORTION CORRESPONDS TO VIEW B OF FIGURE 9)

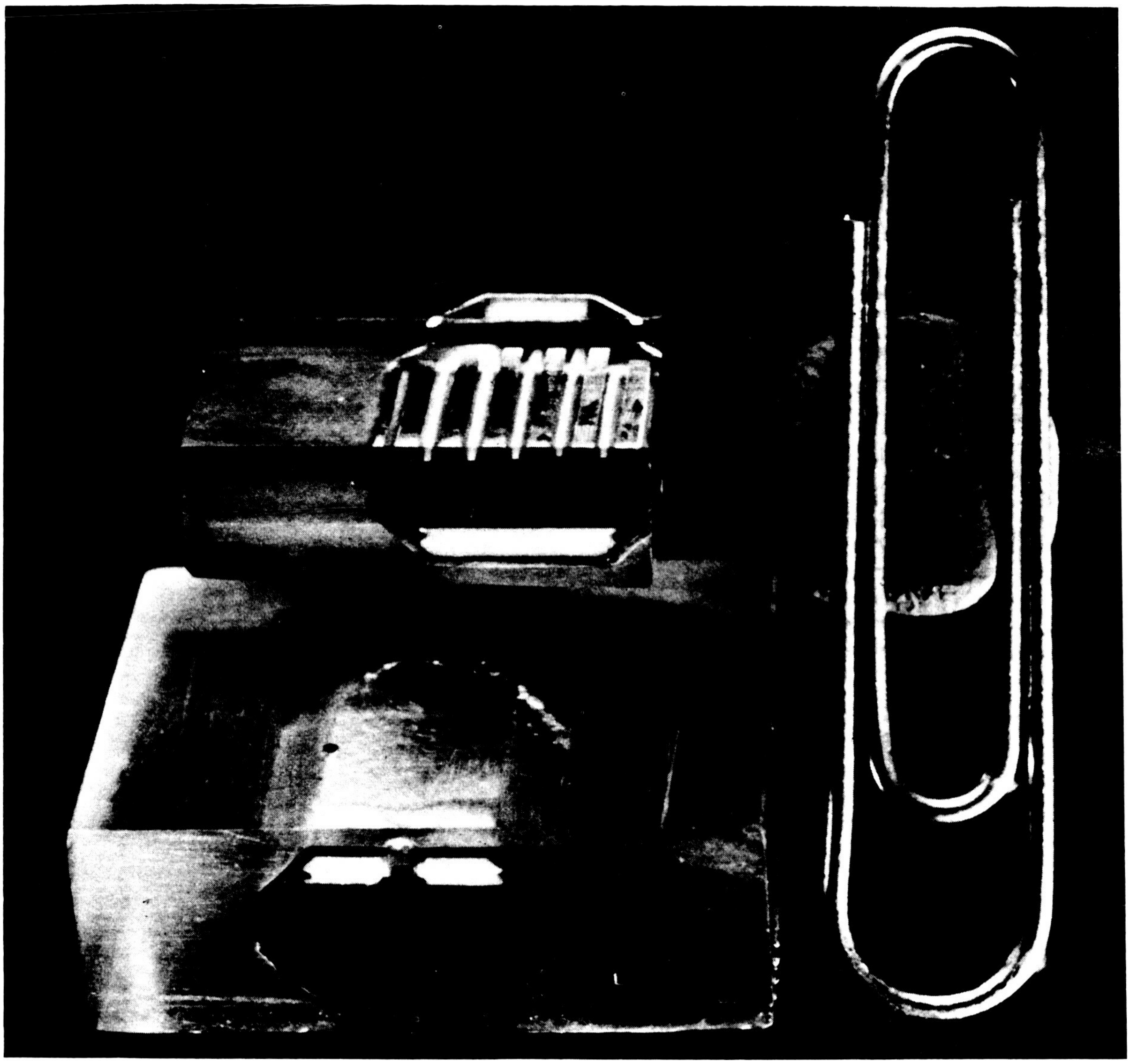


FIGURE 11
CUTAWAY OF ENCAPSULATED DRIFT
TUBE-FOCUS STRUCTURE SHOWING RELATIVE SIZE

The design, and later the fabrication, was more difficult than it would have been had there been cylindrical symmetry. This is perhaps a disadvantage inherent in the use of strip beams.

### 3. Cathode and Gun Structure

The gun structure, (cathode, Pierce electrode, anode) was designed with the aid of Varian's computer program. The starting point of cathode size was determined by allowable cathode loading and required beam size. The finishing point gives all dimensions of all electrodes.

A rectangular pancake heater was designed to fit a recess in the dispenser cathode. A molybdenum frame held the cathode and was in turn supported by four ceramic rods. This ceramic support was chosen as a result of thermal efficiency considerations. The entire support structure was kept as small as possible for weight saving. After early testing, it was clear that serious problems existed with the focusing system. Therefore when the cathode had to be replaced, thermal efficiency considerations were put aside for economy of time and effort and a relatively large standard heater and support structure were used in all future experiments.

### 4. Cavities

The design of cavities was carried out only for the cavities to be used in the first test vehicle. These were designed with a rectangular cross section in all three planes. Wide range tuners would provide a desirable degree of freedom for the first test vehicle and these are more conveniently provided for with rectangular cavities. A final tube would have only trimming tuners and would probably be round. In either case the cavity top and bottom plates would be domed for structural strength.

Stainless steel was used for low Q. The cavity height was fixed by the gap-to-gap distance and the minimum allowable thickness of the common top and bottom plates. The resonant frequency then fixed all other dimensions since the drift tube is to be kept essentially equidistant from all walls.

Tuners were designed and built and a test cavity assembled. R/Q measurements were made using a perturbing dielectric rod and R/Q found to be 44. This comparatively low value results from the close spacing between the top and bottom cavity plates. This in turn is dictated by the gap-to-gap distance chosen to be 90° at the one-watt level. However, if one considers R/Q per unit length as the figure of merit, then no disadvantage exists.

## IV. EXPERIMENTAL WORK

### A. FABRICATION

#### 1. Introduction

The entire fabrication and assembly operation faced the simultaneous challenges of extreme smallness, tight tolerances, and lack of cylindrical symmetry. The small size came somewhat unexpectedly since low S-band tubes are not usually so affected. The 1 watt operating level combined with the hard focused strip beam geometry to fix the dimension 2a (Figure 2) which governed all other dimensions. This size problem existed for the cathode and cathode support structure but was most noticeable in the drift tube-focus structure.

#### 2. Drift Tube Construction

The interdigital vane construction was chosen in addition to other reasons because the vanes would admit of punch press fabrication. However, this method of fabrication is not economical for one tube and the various focus structure parts were machined with few exceptions. Copper was chosen for ease of machining.

The tiny size of most of these parts required holding jigs machined to high tolerance. The word tiny may be given a quantitative meaning by reference to the working drawings of one of the focus electrodes and the edge effect (side) electrode shown in Figures 12 and 13. The same size difficulty existed for the insulating ceramics. The jigs were built and all parts successfully fabricated and made ready for assembly.

Extensive jigging was built for the brazing operations. The assembly procedure outlined in Section III. B. 2. was followed. Little difficulty was encountered

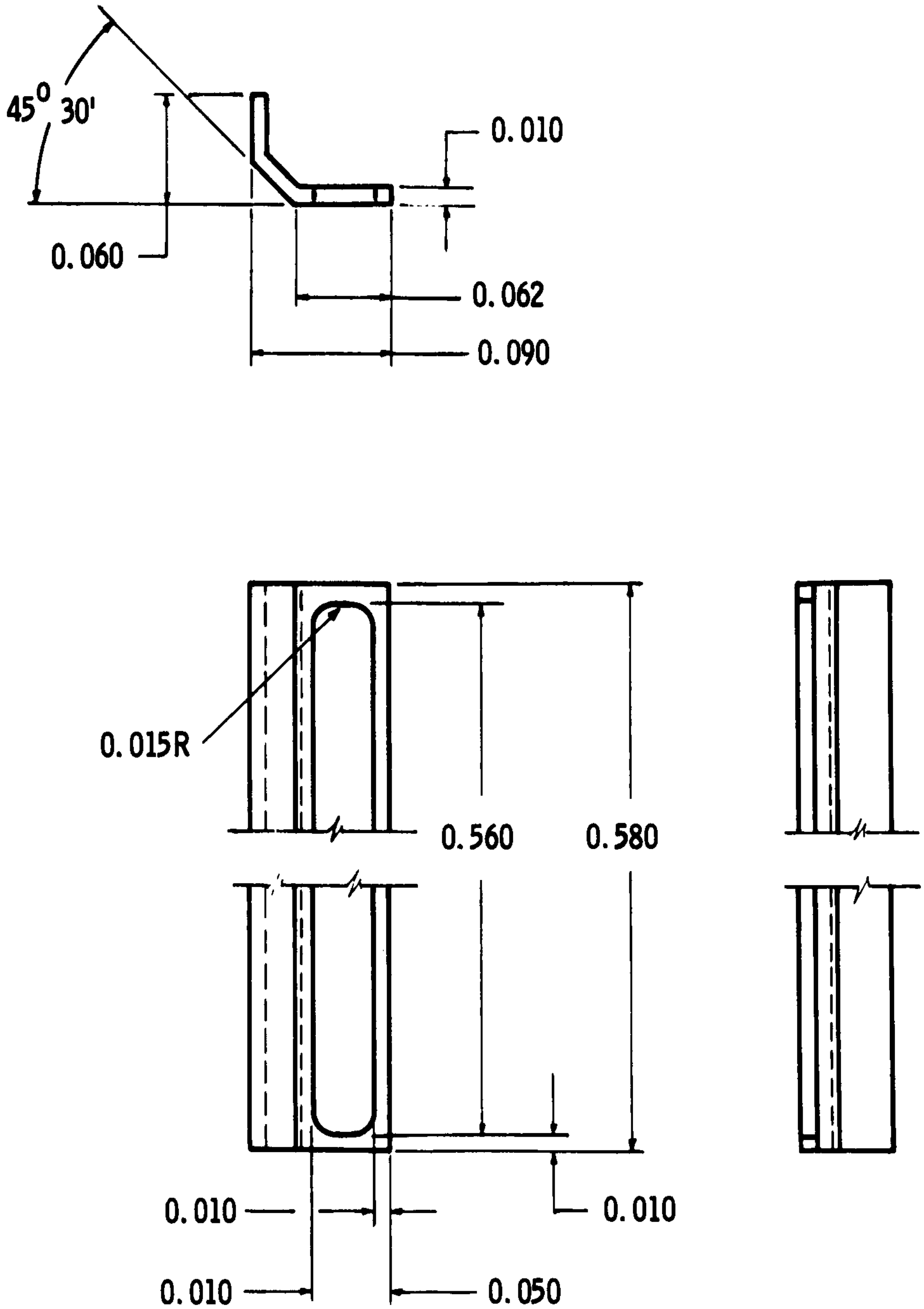



FIGURE 12
NEGATIVE FOCUS ELECTRODE, TYPE B

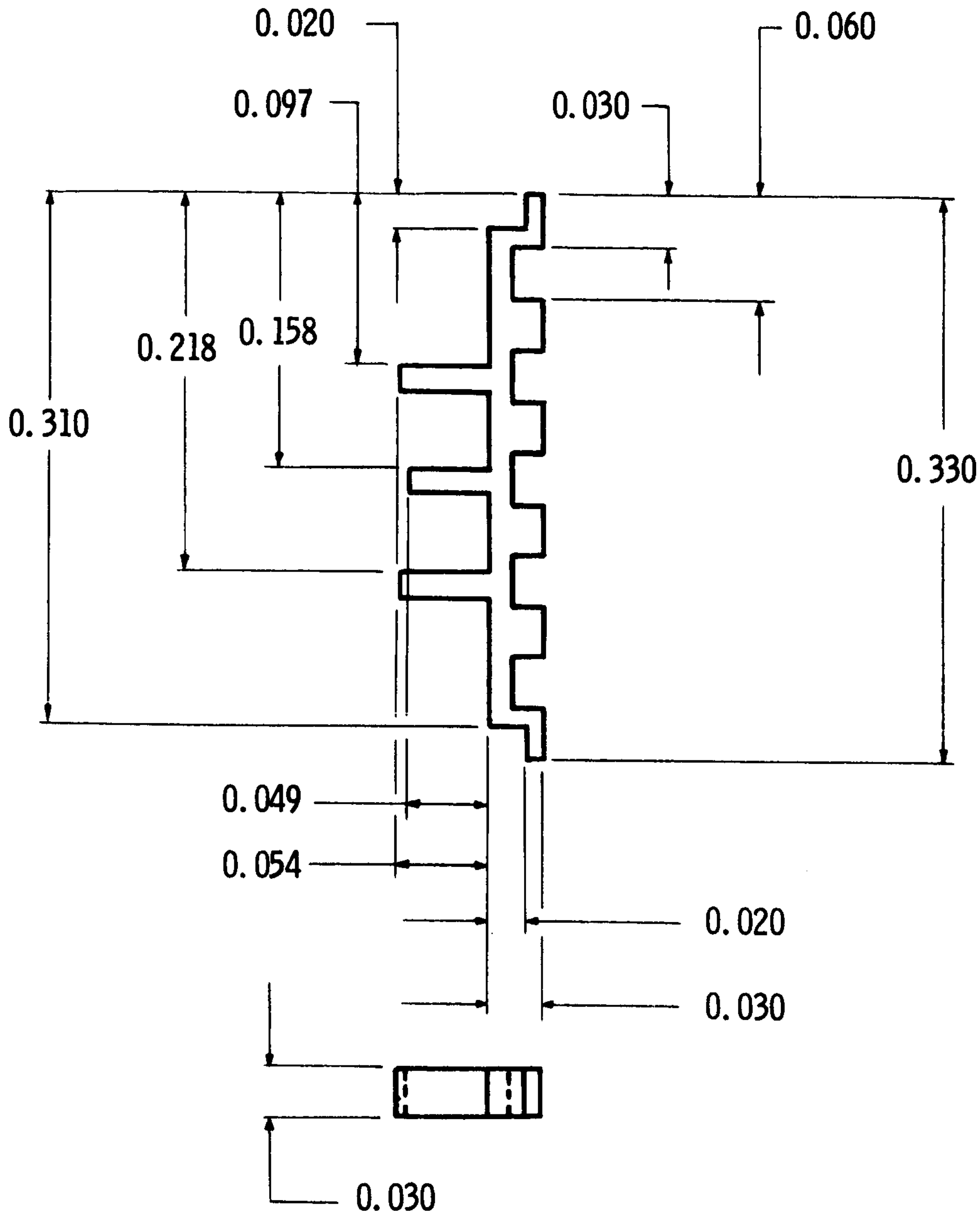



FIGURE 13
EDGE EFFECT ELECTRODE

in steps 1 and 3. Brazing the negative focus electrodes onto the insulating ceramic presented a problem due to the annealing of the 10 mil thick copper electrodes during the braze. The resulting comb-like structure had to be combed with a mating jig to work harden the focus electrodes. The braze operation assembling the edge electrode structure (step 4) suffered from thermal expansion and contraction during braze and required some redesign of the jigs. The final drift tube braze (step 5) was unsuccessful the first time necessitating a jigging modification. These difficulties being solved, the next three complete drift tubes were assembled successfully.

### 3. Assembly of Drift Tube Into Cavity Plate

A completed drift tube was next brazed into its slot in a cavity plate. Serious difficulty was experienced with this braze culminating in a holed drift tube side; the braze material having reacted with the copper; and a cracked insulating ceramic. Experiments were then conducted with a dummy drift tube. The solution included the use of a copper insert in the slot of the stainless steel cavity plate which acted as a stress buffer between the plate and the drift tube and provided for an easier final braze.

At this point in time it was becoming clear from the bell jar type of focusing experiments under way that there were fundamental focusing problems. Further mechanical work toward the completely brazed four-cavity test vehicle was halted while these experiments described in the next section were pursued.

## B. ELECTRICAL EXPERIMENTS

At the midway point in the program, it was decided to avoid some of the difficult fabrication problems referred to in Section IV. A. and to utilize the gun, drift tube and collector assemblies which had already been fabricated for bell jar type focusing experiments. The gun and collector were assembled and these two structures and a drift tube were assembled as the beam tester. See Figure 14. The drift tube-focus structure will be referred to as either the drift tube or the focus structure with the positive portions called positive focus electrodes or body while the negative focus electrodes will be referred to as simply the focus electrodes. Transmission is defined as the ratio of collector current to cathode current.

There were a number of aspects of the demountable nature of these experiments which caused some difficulty. Since the system was not bakeable, cathode activation took considerable time, and the repeated letting down and reactivation of the tube took more time than it would have in a bakeable system. A number of precautions were taken to minimize this difficulty, and as a result vacuum during operation was always held below $10^{-7}$ torr, and in fact typical operating vacuum was closer to $3 \times 10^{-8}$ torr.

1. <u>First Group of Experiments (Gun No. 1)</u>

a. <u>Complete Tester</u>

The beam tester was set up in the bell jar, pumped down, and cathode activation begun.

While the cathode was only partially activated, some data was taken and transmission was found to be 20 per cent. The connection to the focus electrodes developed an intermittent open. The jar was let down, the connection fixed, and cathode activation begun again.

When the cathode reached full activation and transmission was being measured, a side electrode shorted to the focus electrode. Data to this point showed a microperveance of 6.4 and transmission of 10 per cent to 15 per cent. The jar was let down and the shorted drift tube was replaced.

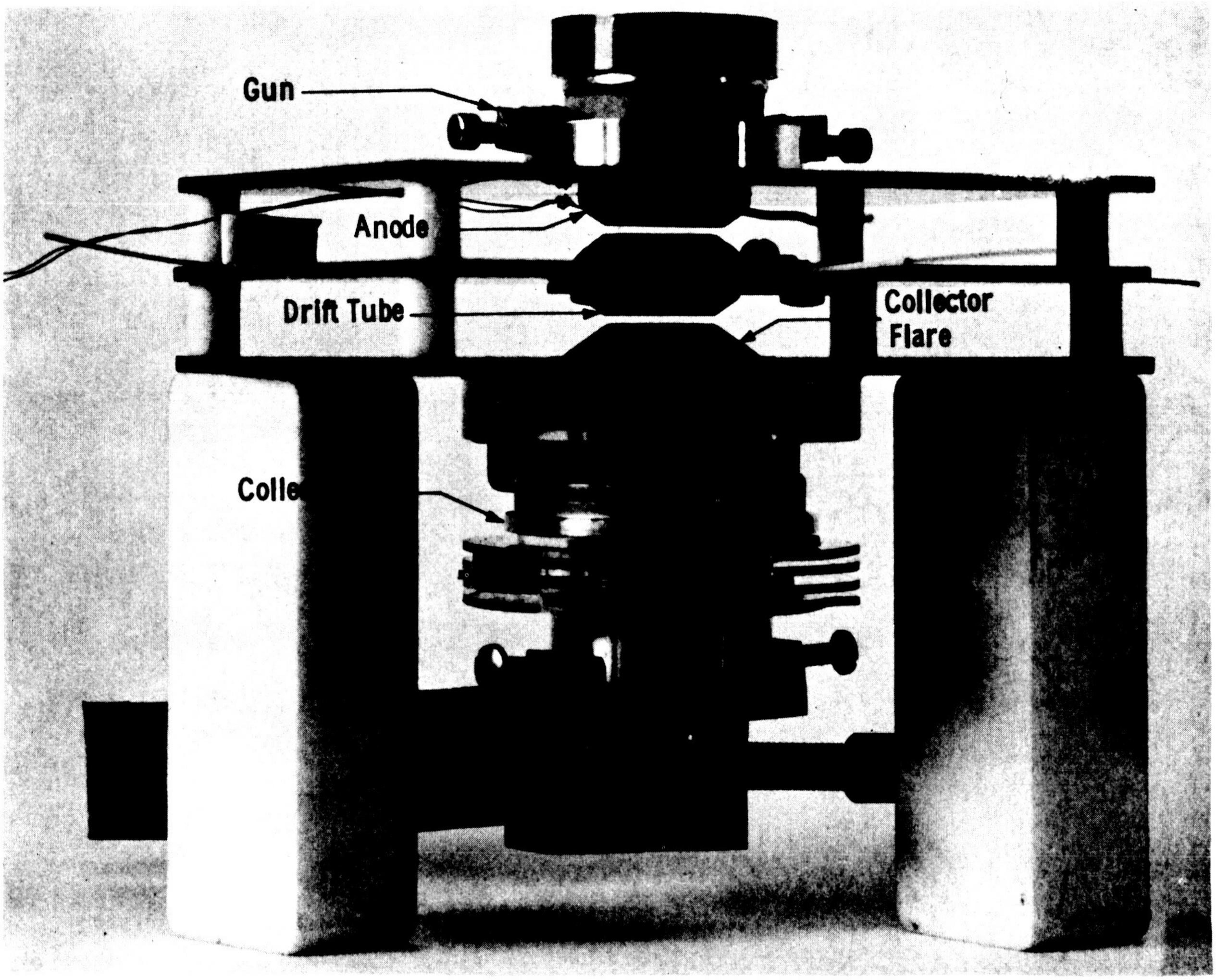



FIGURE 14
BEAM TESTER ASSEMBLY A

b. Complete Tester

After reassembly and processing, gun data and transmission data were taken (Figure 15). While the gun perveance was a very satisfactory 6.25, the transmission was extremely poor. Note, however, that the edge electrode current was only 2 per cent of the current to the collector and 0.2 per cent of cathode current. It would appear that the semi-quantitative arguments used to justify the edge design were essentially correct.

Since anode and body were electrically contiguous, it was necessary at this point to determine whether the major part of the beam current was being intercepted on the focus structure or if it was never getting through the anode.

c. Gun and Collector Only

The drift tube was removed and the collector placed directly beyond the anode. The tester was pumped down, the cathode activated and transmission data taken. Anode transmission was found to be poor, about 70 per cent. The tester was disassembled and the gun inspected. The cathode was found to be tilted slightly with respect to the anode. This was corrected, the gun and tester reassembled, pumped down, and activated. The microperveance was 6.2 and transmission data being taken when the cathode developed a serious leak to the anode. Up to this point transmission was 95 per cent.

d. Complete Tester

At this time heavy leakage was found between the cathode and anode pins on the vacuum side of the feedthrough. In addition the cathode was showing some signs of aging, and the heater, having already required repair, was in dangerous condition. Figure 16 shows some data taken under these conditions of marginal operation, and is included specifically to show the split of current between anode and body. It was again clear that the major interception was on the body, that is, in the focusing

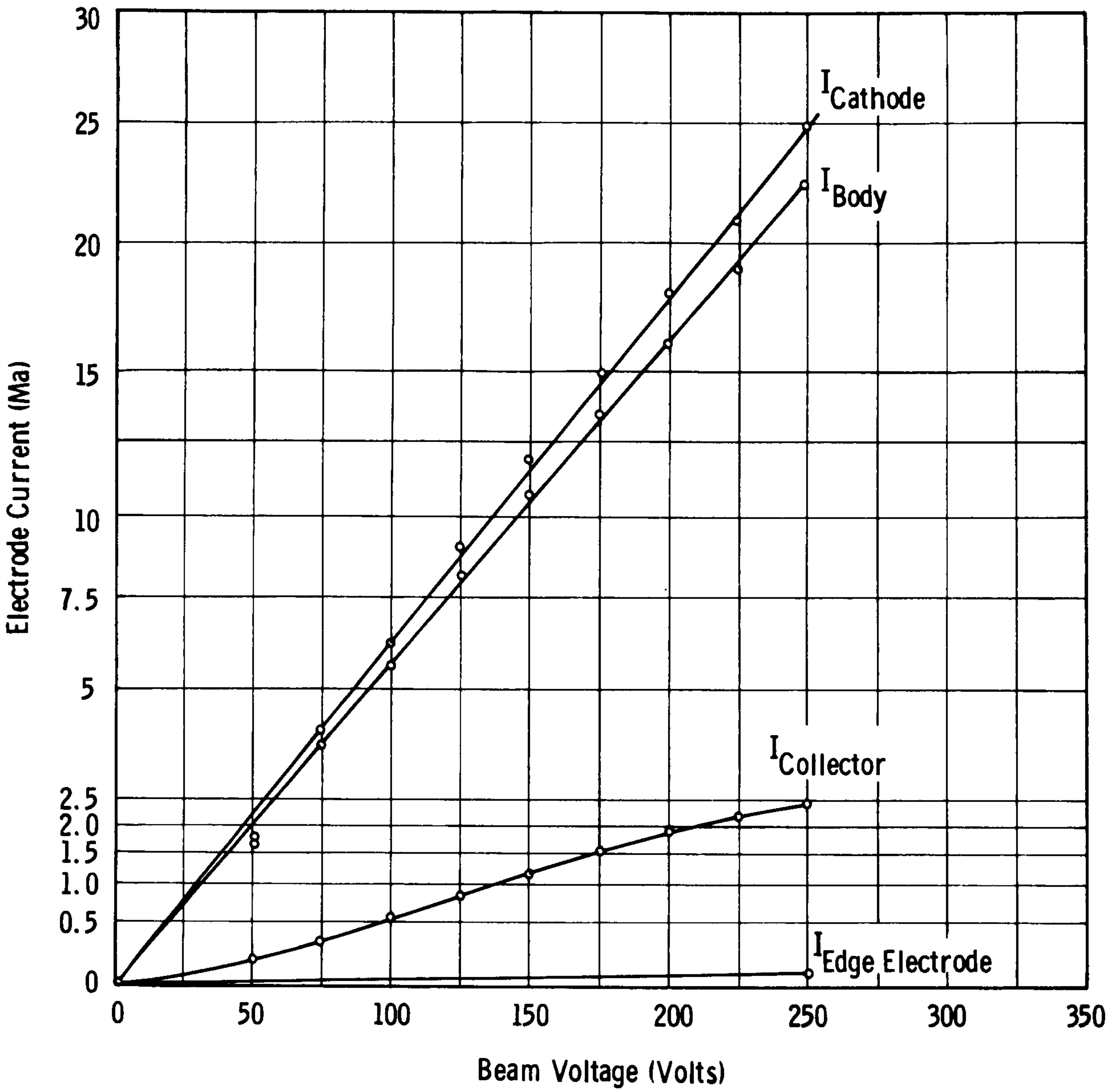



FIGURE 15
CURRENT DISTRIBUTION VS BEAM VOLTAGE, BEAM TESTER A

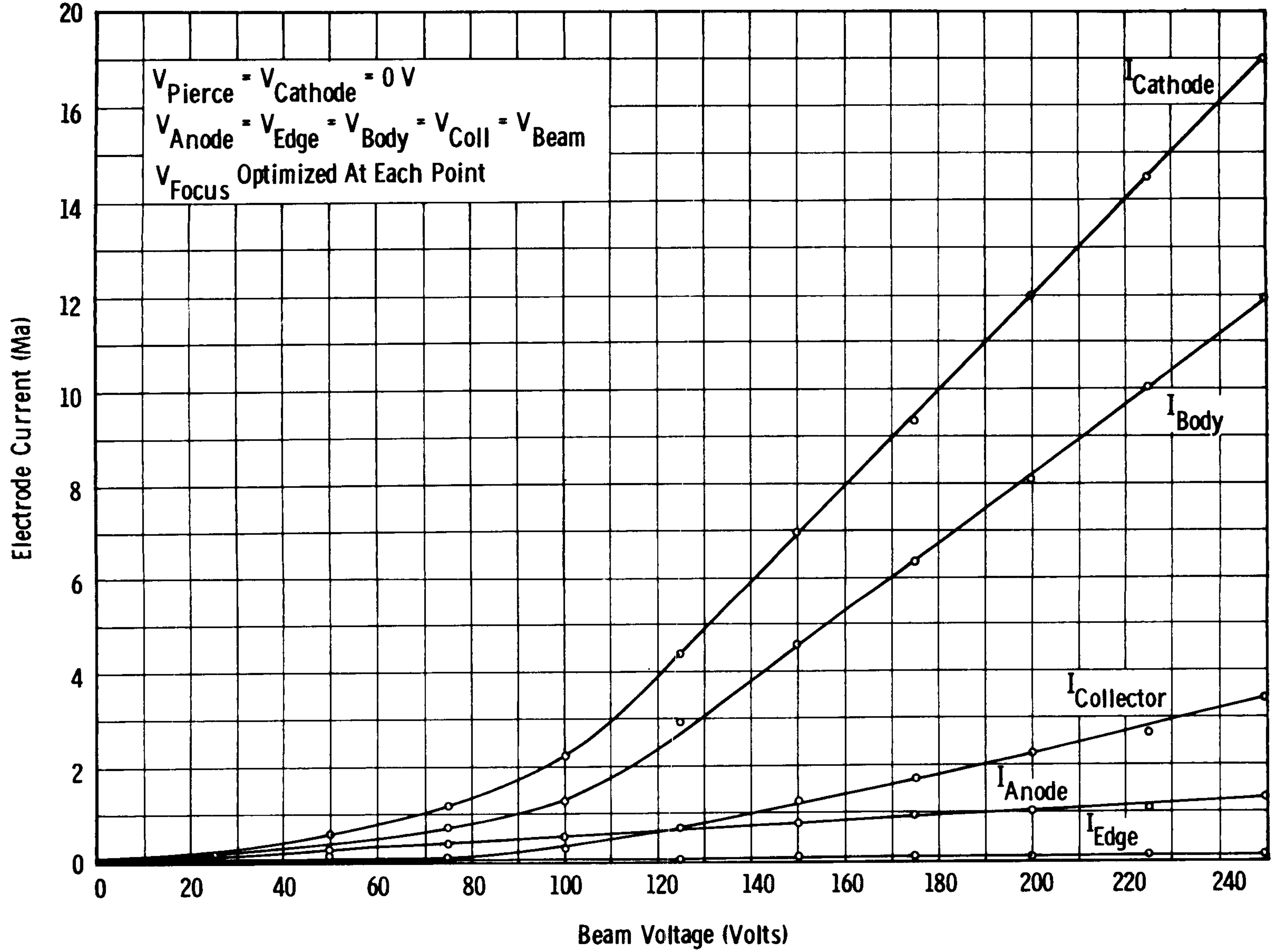



FIGURE 16
CURRENT DISTRIBUTION VS BEAM VOLTAGE, BEAM TESTER A

structure. However, the cathode was behaving poorly, and at this point it was decided to redesign the heater and cathode support structure, as shown in Figure 17. This configuration uses a rugged, high power heater from factory stock. Ignoring for the present time the problem of heater efficiency, advantage was taken of this reworking period to insulate the Pierce electrode from the cathode to allow separate voltage control.

Study and consideration of the data taken up to this time led to the conclusion that alignment was critical, much more critical than had been suspected. This problem of very accurate alignment, caused in part by the long, narrow beam of small size, was aggravated by the prohibition against normal jigging techniques. This was due in part to the absence of cylindrical symmetry and more particularly by the inability to use a mandrel through the drift tube. The focus electrodes were of 0.010 inch copper sheet and would be bent out of shape should the mandrel drag in the slightest amount. Thus the drift tube was aligned with the anode by less effective methods. Considerable effort was expended to make these methods more effective. Since all previous data were taken with a misaligned cathode and then with a sick cathode, there was reasonable hope that the poor transmission was caused simply by poor entrance conditions which would now be corrected. The fabrication of gun and jigs was completed, a heater calibration curve run, and the beam tester reassembled.

### 2. Second Group of Experiments (Gun No. 2)

#### a. Gun and Collector Only

The output flare portion of the collector was identical in size, shape, and location with respect to the anode, to the first positive electrode when the drift tube was in the assembly. Since the output flare was insulated, its interception could be measured and information gained with regard to beam entrance conditions. Specifically, one could learn if the major portion of the beam was getting fairly into the focus structure.

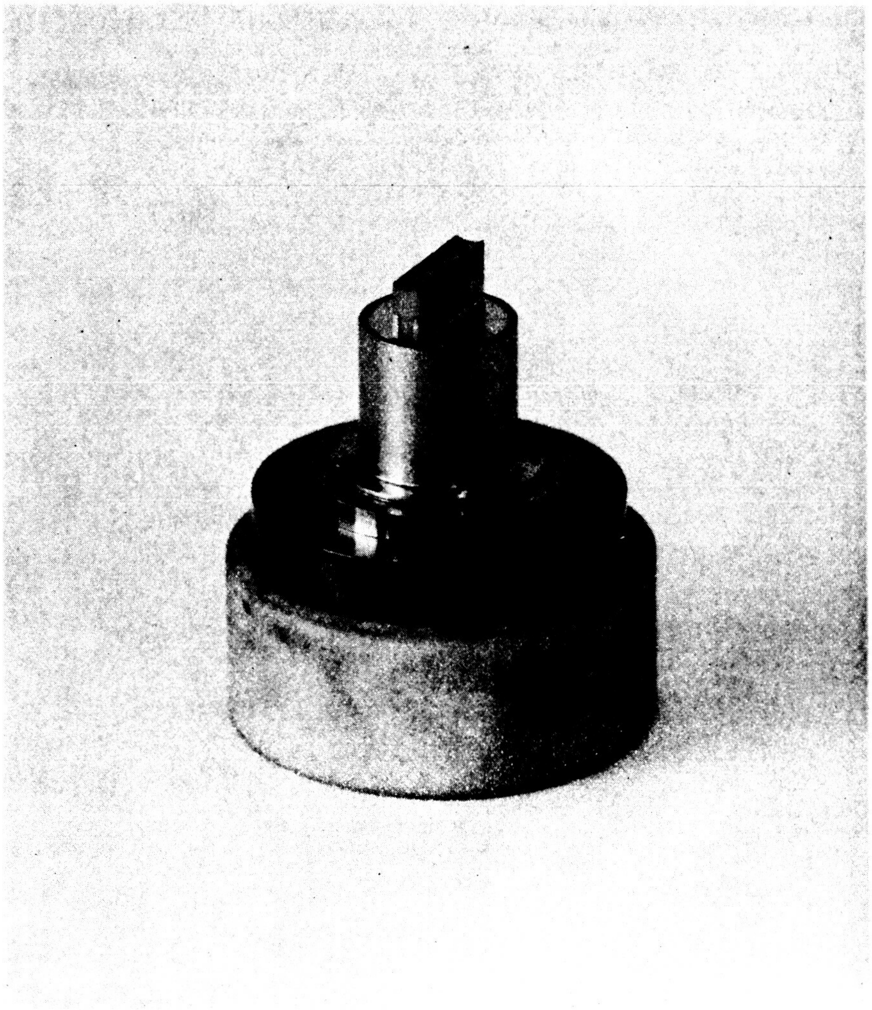


FIGURE 17
REPLACEMENT GUN STRUCTURE SHOWING CATHODE SHAPE

The first attempt at taking data, disclosed leakage across the ceramic supporting the Pierce electrode from the anode. The ceramic was sand-blasted and tester reassembled, pumped down, and activated. Transmission to the collector was over 90 per cent and current to the output flare was less than 5 per cent of the cathode current. This improvement in the data gave convincing evidence for our belief that even in the gun mechanical alignment was a very critical factor. At this point we felt that gun alignment could with care be held to the required value. The experimental work then returned to study of the focus structure.

b. Gun, Focus Structure, and Collector

The jar was let down and the focus structure assembled in the tester. Transmission was still poor and an effort was made to vary the entrance conditions. It was found that transmission could be improved by running the body and collector positive with respect to the anode (see Figure 18). This positive voltage between body and anode changed the entrance fields and also of course meant that the beam perveance in the focus structure was reduced. In an effort to determine which of these effects was improving the transmission, transmission data were taken as a function of focus voltage for a family of anode voltages with the body voltage held constant. Now the strength of the focusing fields was determined by the voltage between the positive focus electrodes and the negative focus electrodes. If the improved transmission was due to the decrease in perveance, then the optimum focusing field strength would be a function of perveance. However, the optimum focus voltage was relatively independent of beam perveance in the focus structure (Figure 19). While the collector current varied by a factor of 7, the optimum focus voltage varied by less than 20 per cent. In addition, the current intercepted by the collector flare was less than 1 per cent of the collector current indicating that the beam was fairly well focused after passing through the drift tube and would be well launched into the second drift tube. Both of these pieces of evidence indicated that the beam was being improperly launched from the gun even though anode interception was slight and perveance correct.

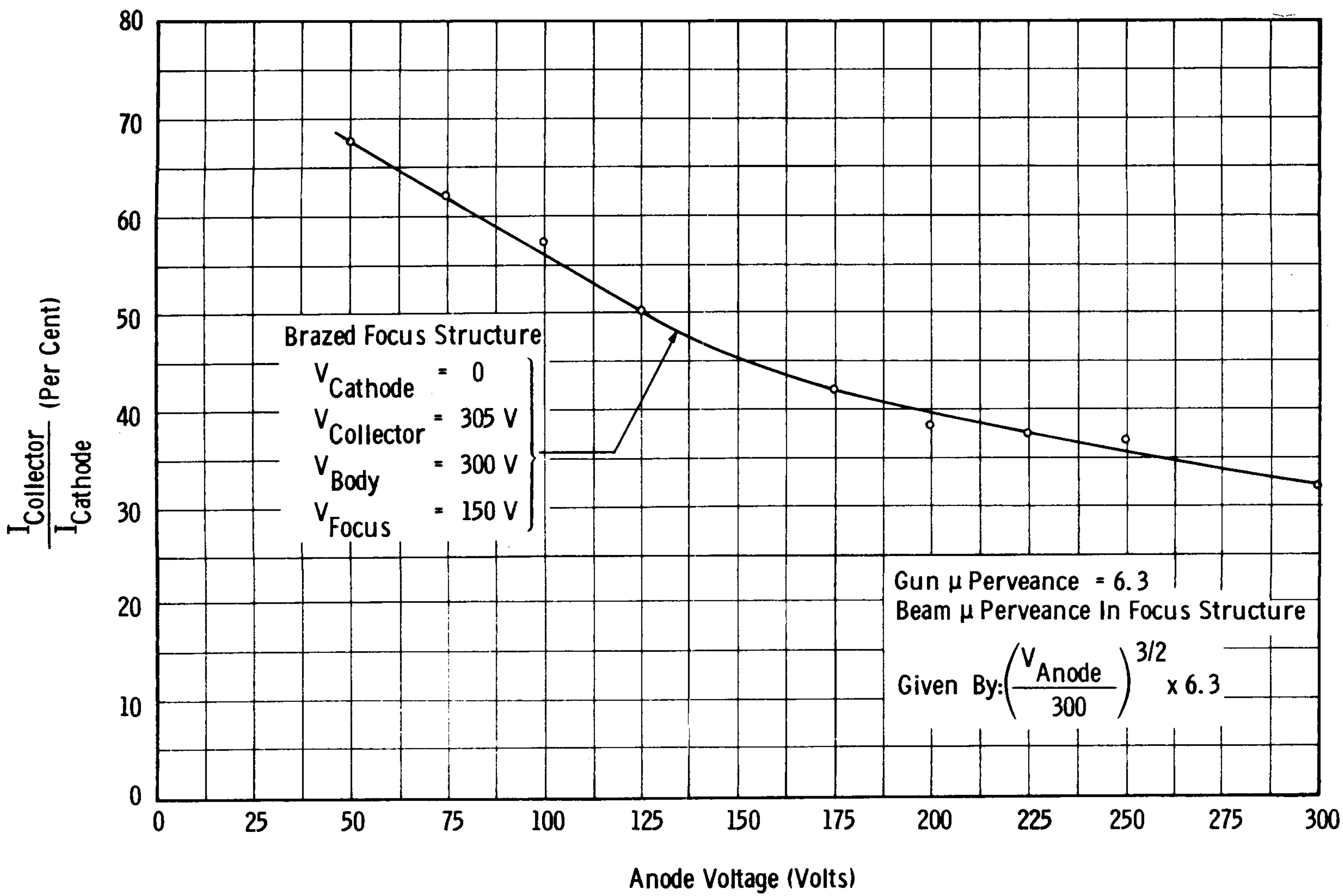



FIGURE 18
TRANSMISSION VS ANODE VOLTAGE FOR CONSTANT BODY VOLTAGE, BEAM TESTER A

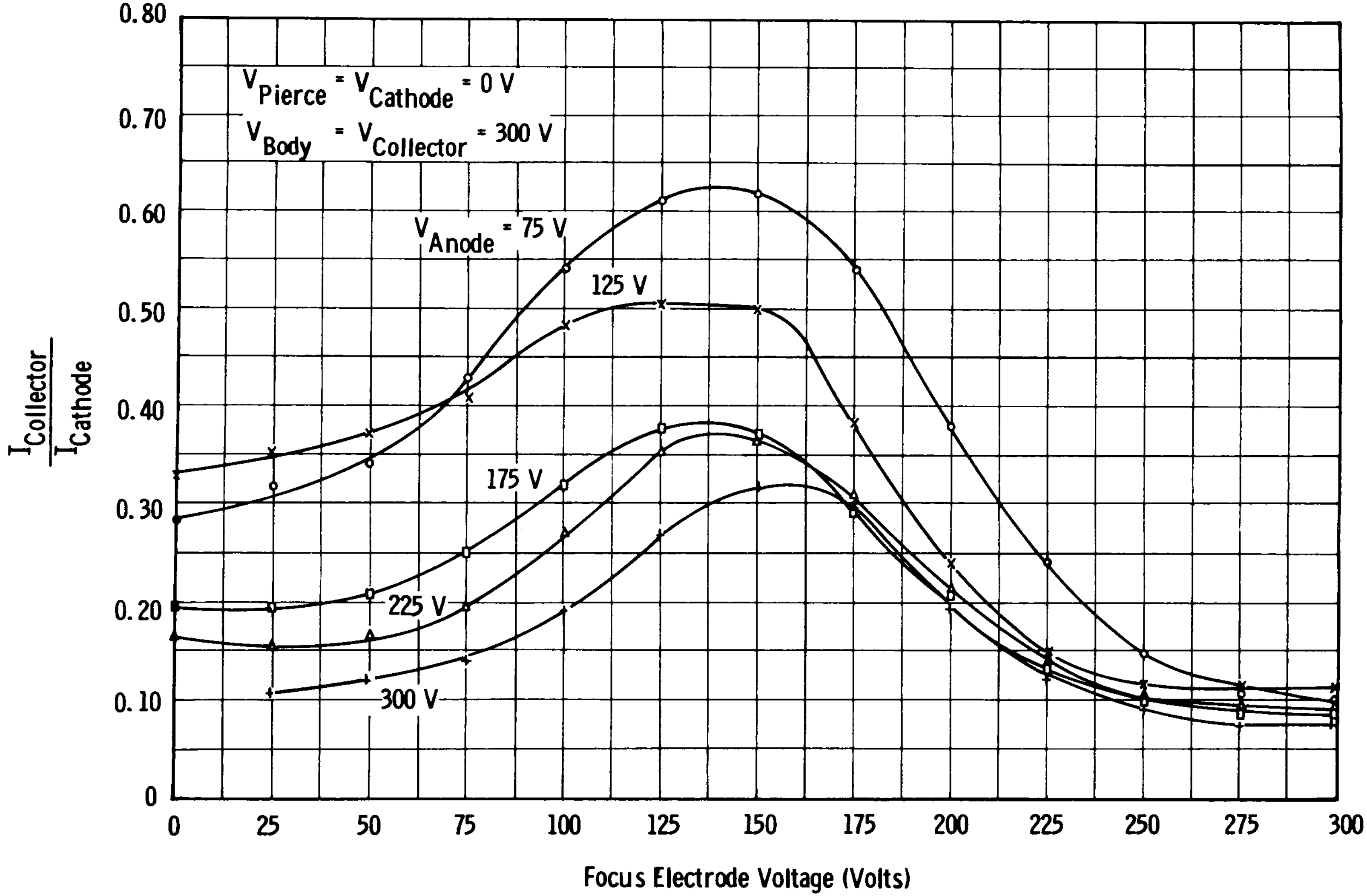



FIGURE 19
TRANSMISSION VS FOCUS ELECTRODE VOLTAGE
FOR A FAMILY OF ANODE VOLTAGES
WITH CONSTANT BODY VOLTAGE, BEAM TESTER A

A second method of changing the entrance conditions was available through the Pierce electrode voltage. A negative voltage on this electrode will tend to compress the beam as it leaves the cathode and perhaps afford a better start into the drift tube. Except for the expected decrease in cathode current, which was down 20 per cent at -15 volts, there was little effect (Figure 20).

Both groups of data given above, admit of the possibility that alignment was still not satisfactory. This would explain in particular the relative independence of current distribution to Pierce electrode voltage. If the interception was due to the center line of the cathode being not coincident with the center line of the anode and drift tube, then the Pierce electrode would have little effect. Alternatively, the poor transmission may be due to more fundamental problems.

### 3. Third Group of Experiments (Gun No. 2 and Isolated Focus Structure)

#### a. Gun, Focus Structure, and Collector (Tester B)

To ascertain further the behavior of the beam in the focus structure it was decided to build a focus structure with individually insulated electrodes. See Figure 21. This structure could be built quickly and economically, would allow the use of a mandrel for alignment and would provide further data on beam behavior in the focus structure. The freedom to adjust individual electrode voltages would also allow further control over beam entrance conditions. The structure was built and a sketch showing nomenclature is given in Figure 22.

The new structure was assembled, pumped down and activated. Initial data were taken for comparison with the behavior of the brazed focus structure. The data stopped at 550 volts as it had throughout most of the experiments. This was required by the thermal problems of insulated elements in a vacuum bell jar. The perveance at the higher voltages was slightly less than design value, being due to the cathode having been let down to air several times during the experiments. It was

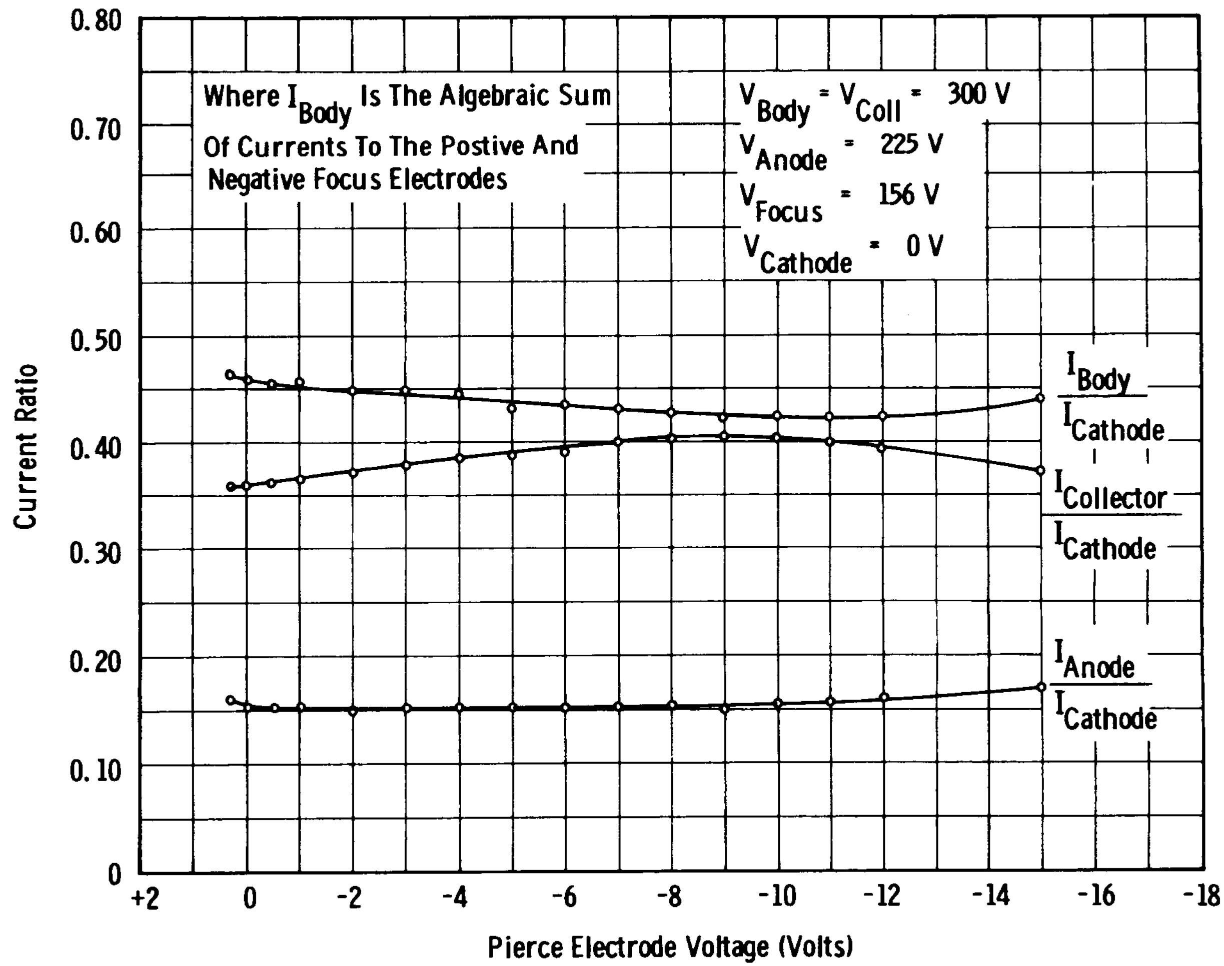



FIGURE 20
BEAM CURRENT DISTRIBUTION VS PIERCE ELECTRODE VOLTAGE, BEAM TESTER A

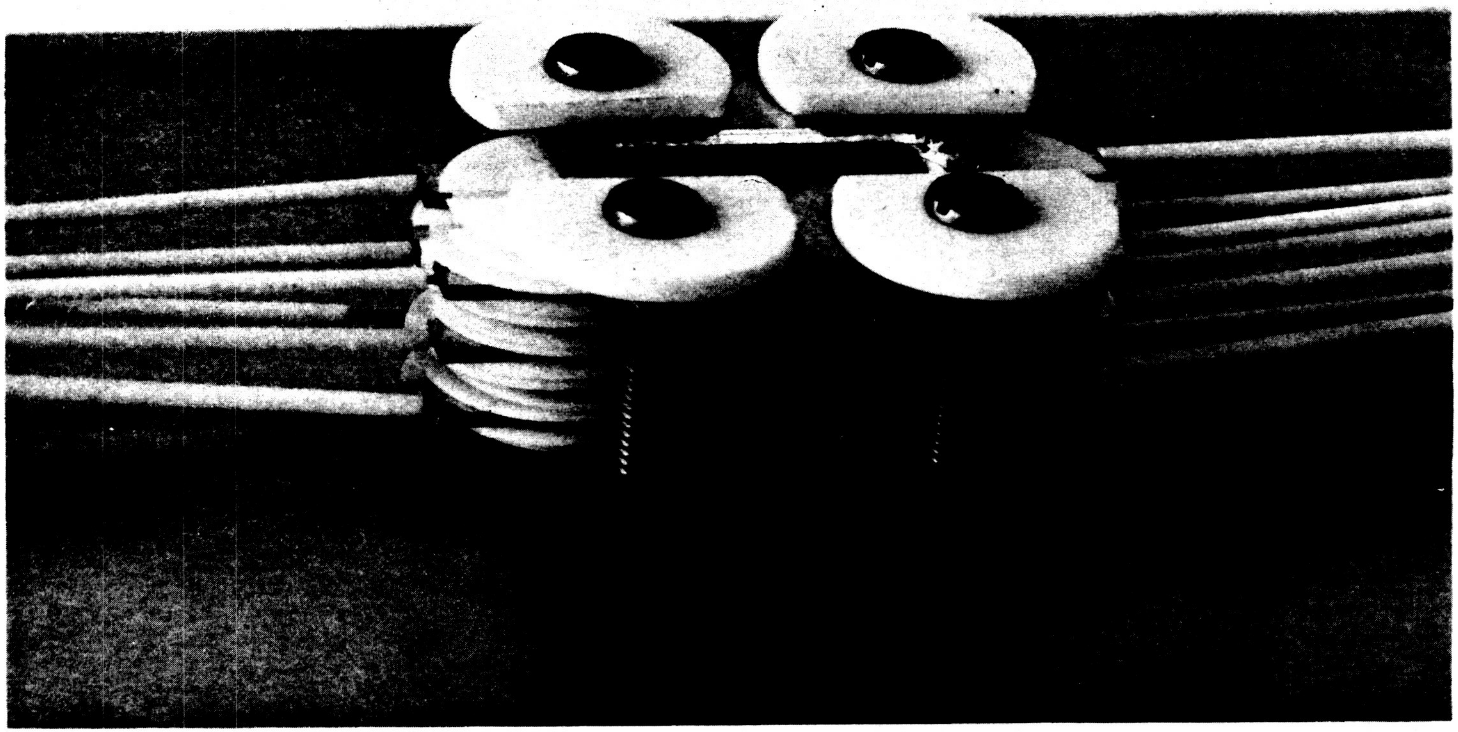


FIGURE 21
MULTI-PLATE DRIFT TUBE-FOCUS STRUCTURE, BEAM TESTER B

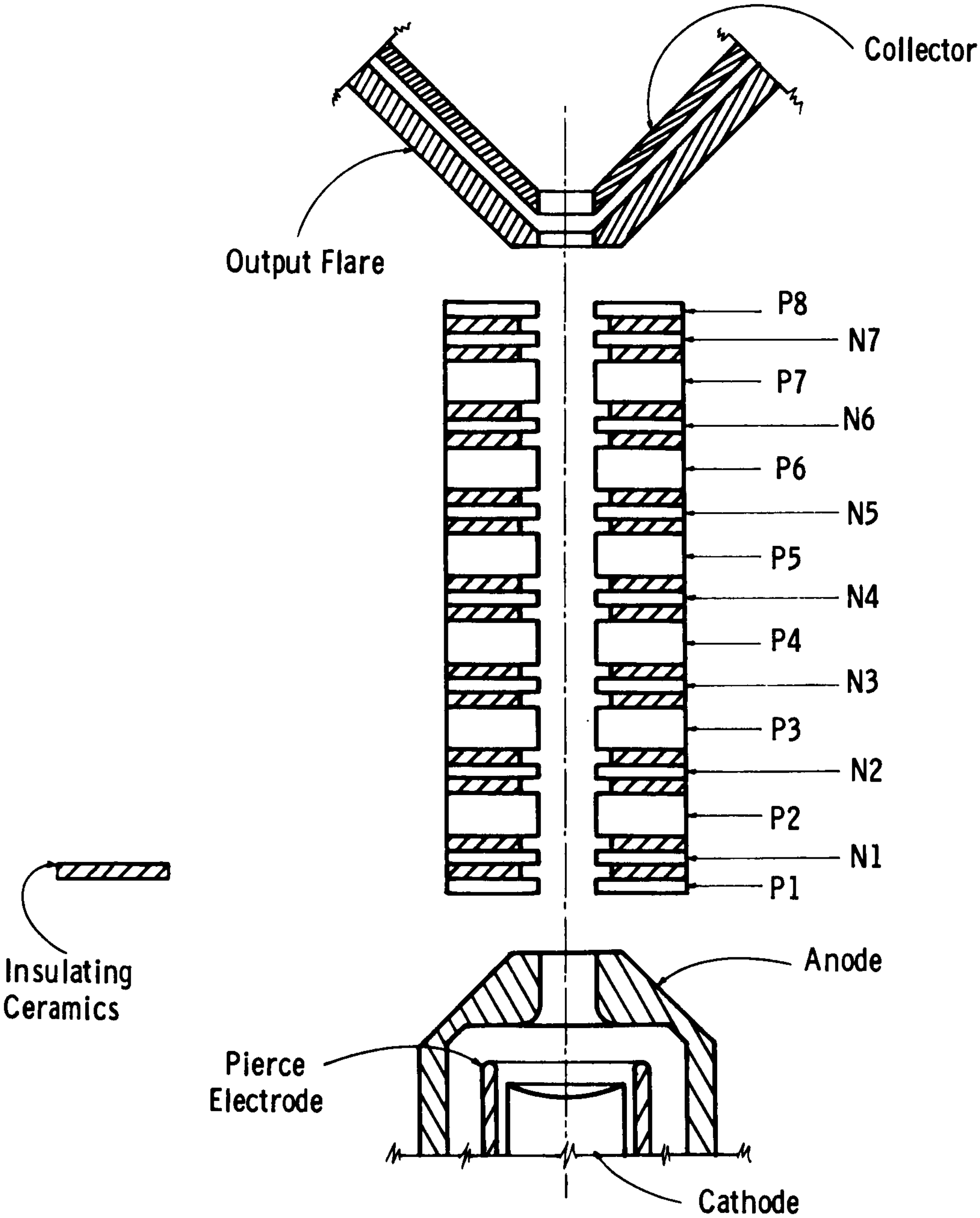



FIGURE 22
CROSS SECTION OF MULTI-PLATE DRIFT TUBE, BEAM TESTER B

immediately evident that transmission was considerably improved but that the best performance did not occur at the design voltages. It was again found that transmission was improved when the body and collector were run at a potential higher than the anode and the focus voltage at a point between cathode and body. The extent of the improvement may be seen from Figure 23 as compared with Figure 18. It seems clear that this is due to better alignment of the elements of the beam tester.

The anode current was not as low as it had been on at least one prior experiment. The gun was apparently still misaligned with respect to the anode. The beam tester was disassembled, and the gun structure inspected. When the cathode face indicated several mils tilt, a close inspection was made and one of the copper cups on the gun ceramic was found to be slightly crushed. The gun structure was repaired. The tester assembled, pumped down, and the cathode reactivated.

b. Gun, Focus Structure, and Collector

Transmission was measured as a function of focus voltage for a family of beam currents (Figure 24). These curves may be compared to those of Figure 19 which were taken with the brazed structure. It is again notable that the optimum focus voltage was relatively independent of beam current. This means that the focusing was independent of space-charge forces at least through the range of beam currents shown.

Data were then taken as a function of beam voltage for a family of anode voltages. This was done with the focus electrodes tied to the cathode and then with the focus voltage optimized at each point (Figures 25 and 26). The shapes of the curves were the same as in previous experiments and the same as each other. The focusing was, however, much improved, a microperveance 1.0 beam having 98 per cent transmission and a microperveance 5.0 beam having 85 per cent transmission.

An attempt was made to improve the launching of the beam by varying the voltage on the Pierce electrode. There was no appreciable improvement, as shown in Figures 27 and 28.

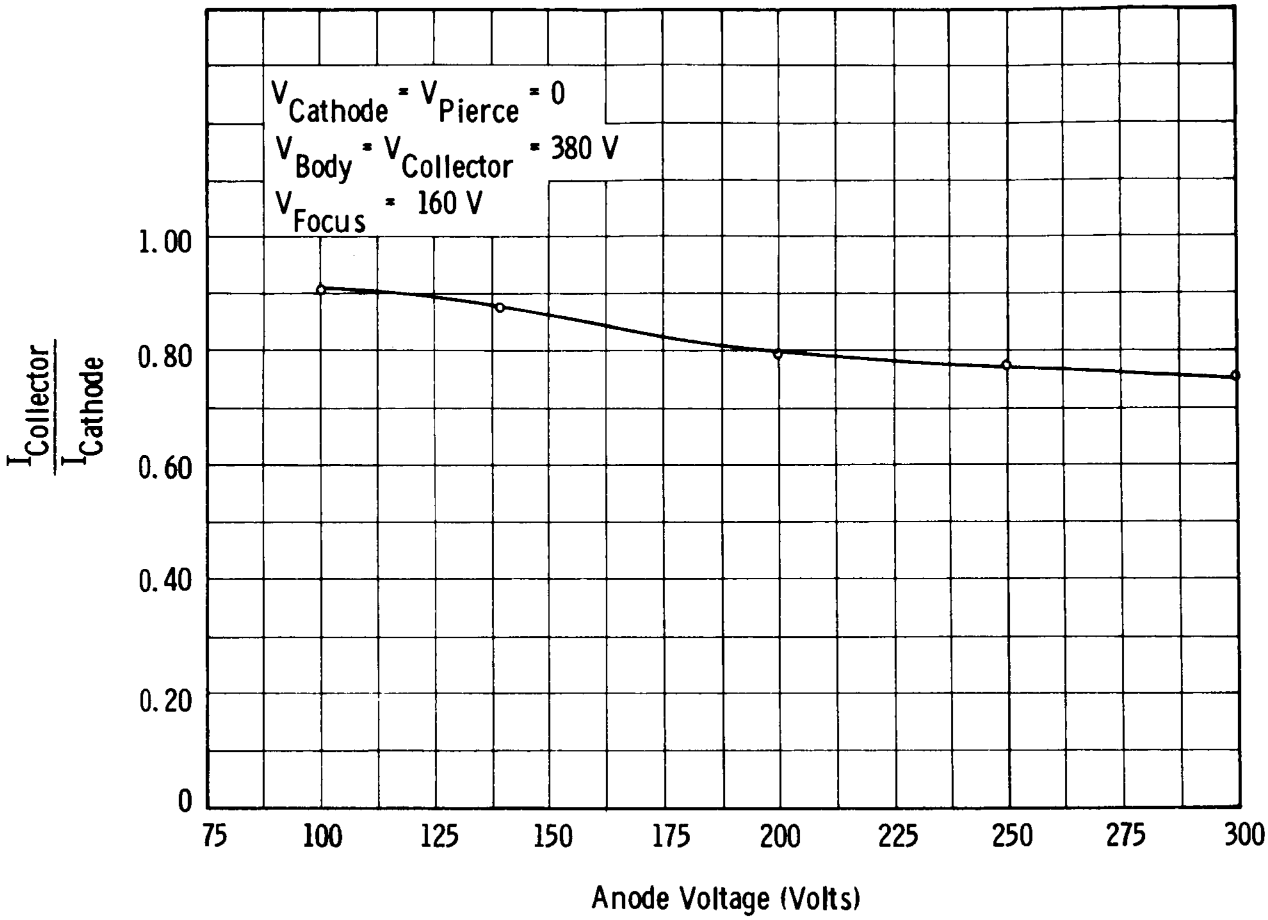



FIGURE 23
TRANSMISSION VS ANODE VOLTAGE, BEAM TESTER B

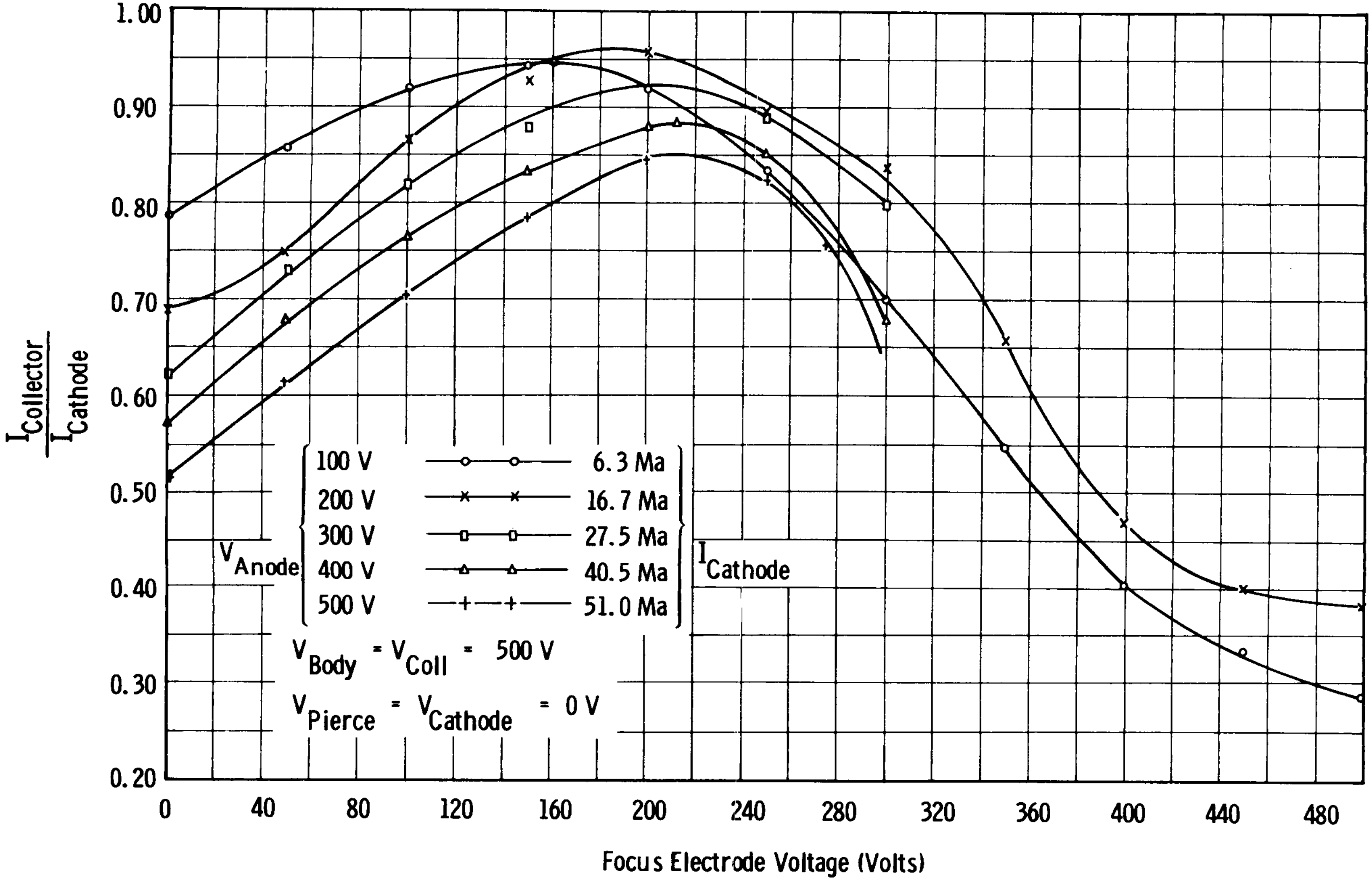



FIGURE 24
TRANSMISSION VS FOCUS ELECTRODE VOLTAGE
FOR A FAMILY OF ANODE VOLTAGES
WITH CONSTANT BODY VOLTAGE, BEAM TESTER B

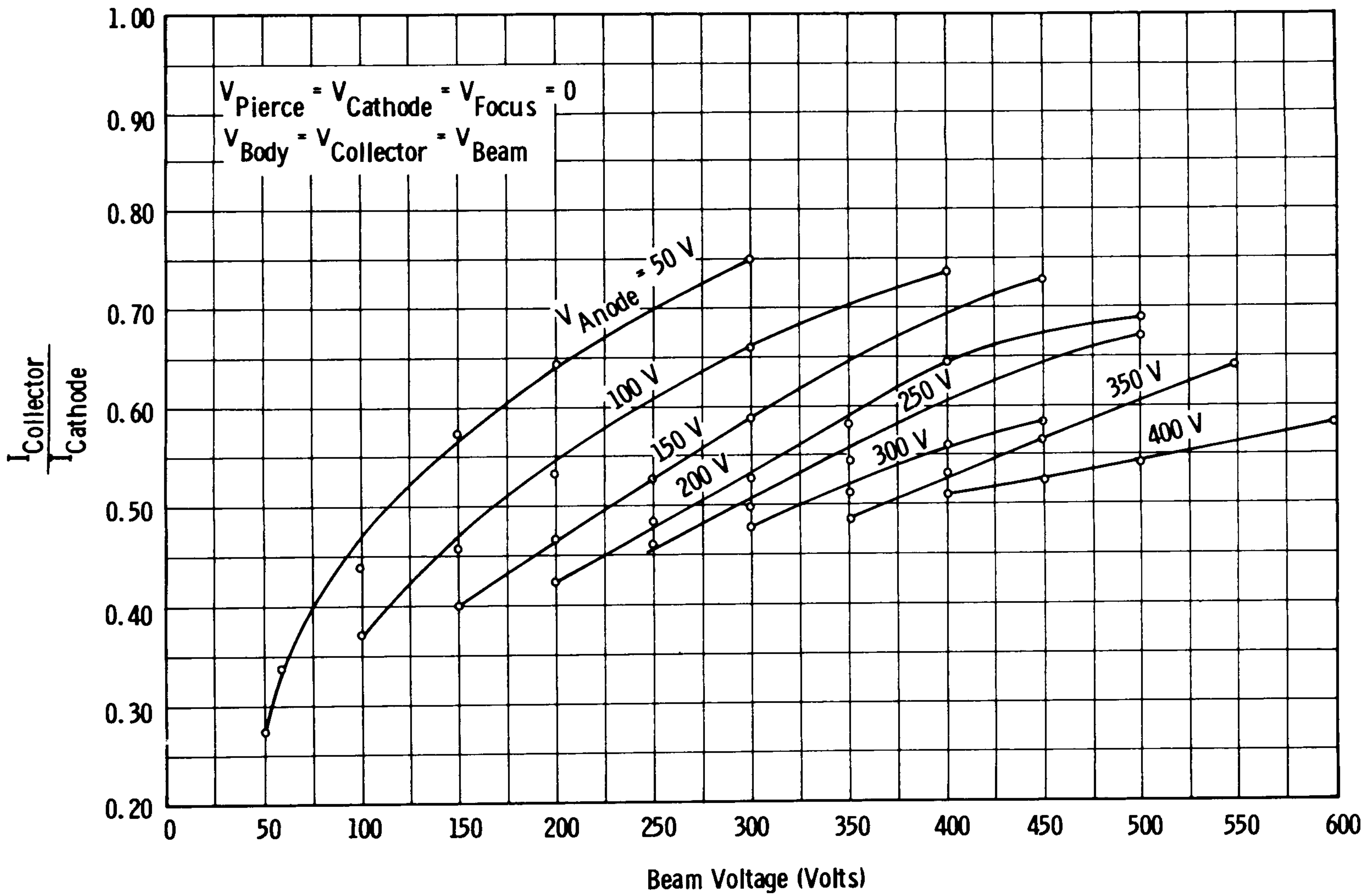



FIGURE 25
TRANSMISSION VS BEAM VOLTAGE FOR A FAMILY OF ANODE VOLTAGES WITH $V_{Focus} = V_{Cathode}$, BEAM TESTER B

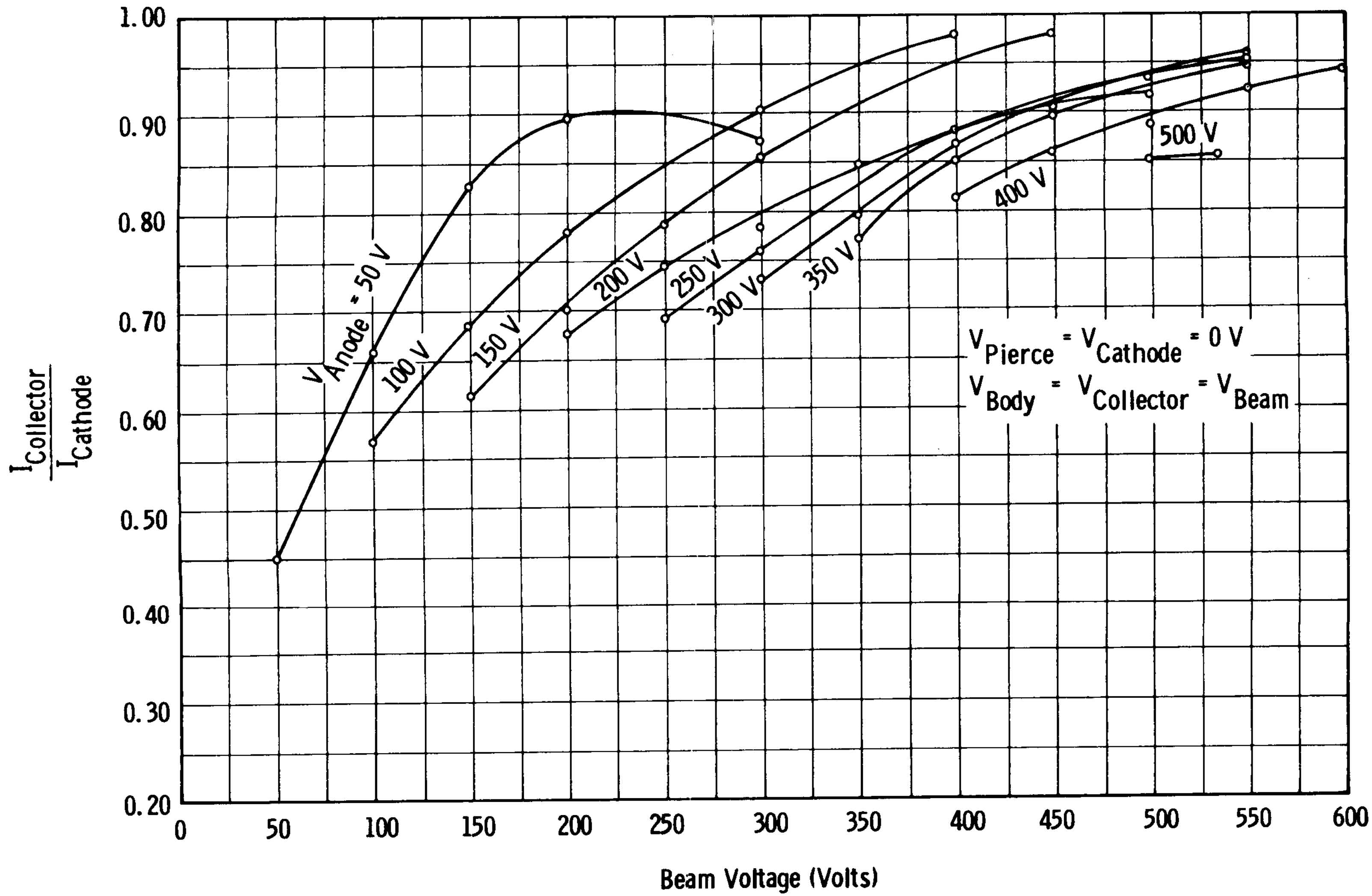



FIGURE 26
TRANSMISSION VS BEAM VOLTAGE FOR A FAMILY OF ANODE VOLTAGES WITH $V_{Focus}$ OPTIMIZED AT EACH POINT, BEAM TESTER B

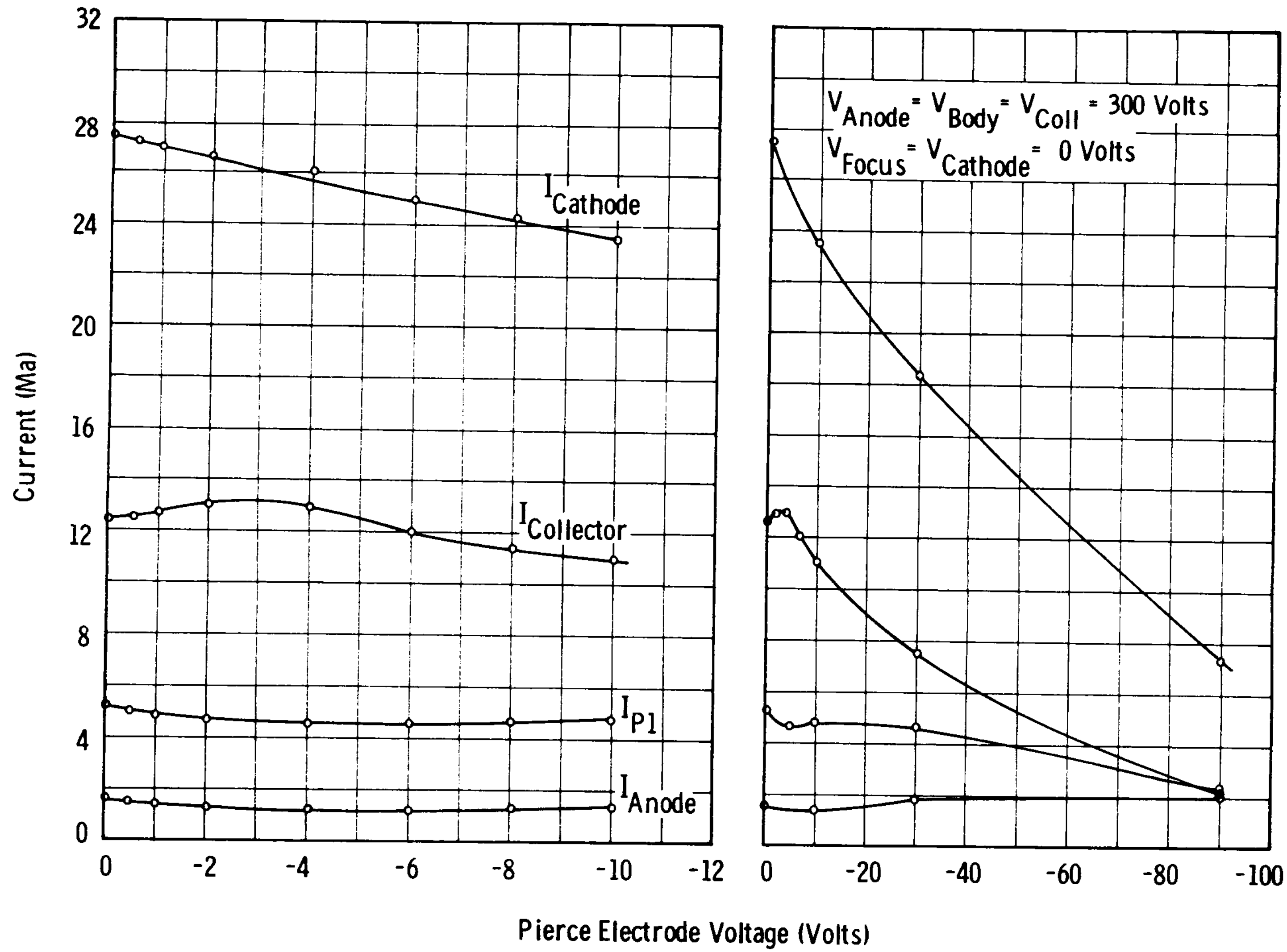



FIGURE 27
EFFECT OF PIERCE ELECTRODE VOLTAGE ON BEAM CURRENT DISTRIBUTION FOR $V_{Focus} = V_{Cathode}$, BEAM TESTER B

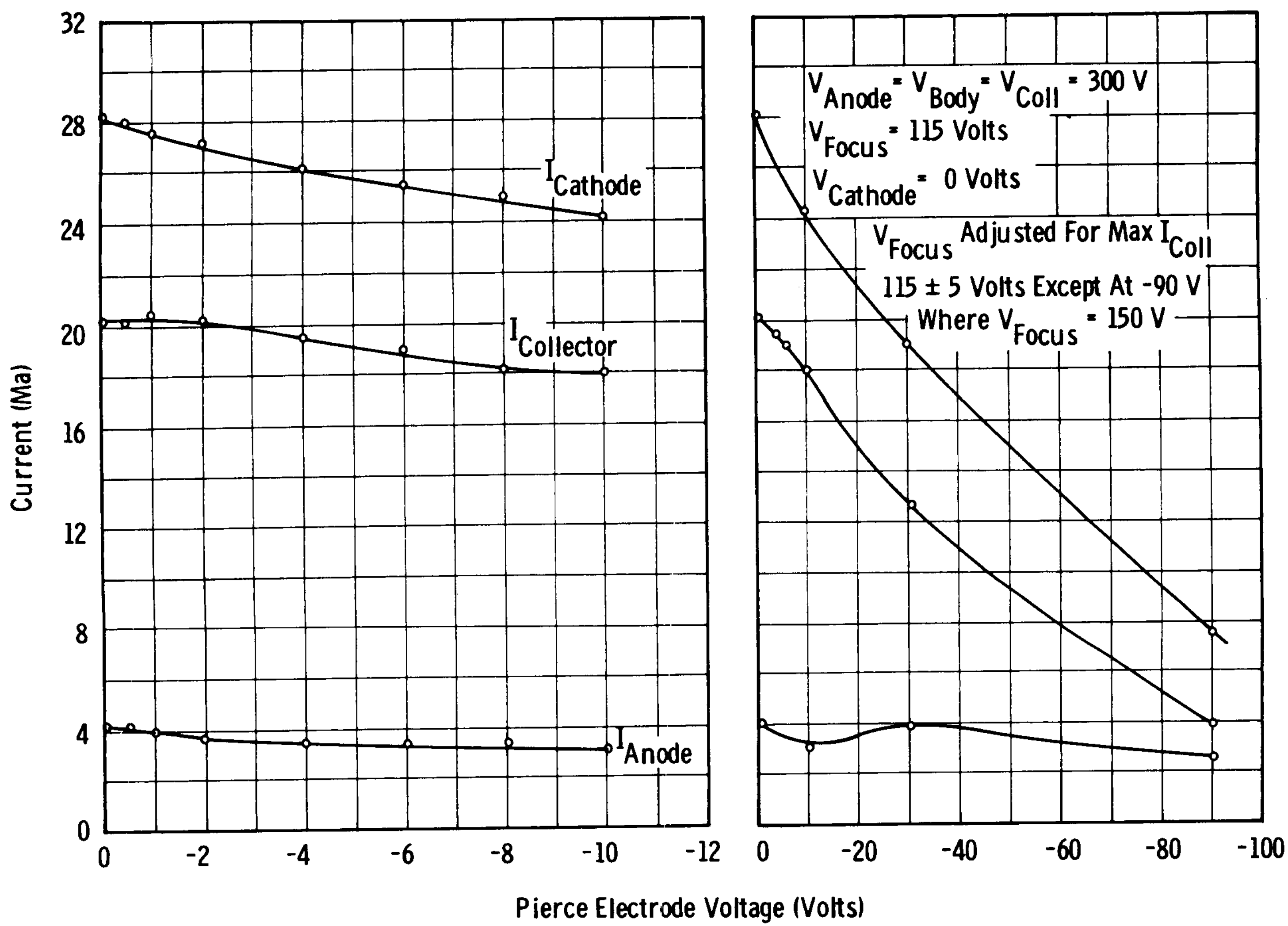



FIGURE 28
EFFECT OF PIERCE ELECTRODE VOLTAGE
ON BEAM CURRENT DISTRIBUTION FOR $V_{Focus}$
OPTIMIZED AT EACH POINT, BEAM TESTER B

Since it was still true that transmission was improved by operating the body and collector at a higher voltage than the anode, and since this did in fact have the effect of lowering the perveance, temperature-limited emission data were taken to see what effect this means of lowering perveance would have on transmission. Figure 29 makes it clear that the focusing is essentially independent of beam perveance.

The current distribution along the focus structure was much the same regardless of anode or beam voltages. A representative distribution is shown in Figure 30. As long as the positive focus electrodes were kept at any one potential and the negative focus electrodes at cathode potential, the distribution remained essentially as shown. When the negative focus electrodes were still tied together, but at the optimum focus voltage, the distribution was not drastically altered (Figure 31). Figure 31 is representative of all distributions when $V_{focus}$ was optimized.

Varying the voltages to individual electrodes did not improve transmission significantly. Slight improvements in transmission could sometimes be made by trimming up each electrode voltage but never more than a few per cent.

The improvement obtained by running the body and collector at a higher voltage than the anode is interesting from a diagnostic point of view but not from a practical one. The improvement achieved by running the focus electrodes at a voltage different from cathode voltage is of more practical interest. First, this could be an operating condition in a working tube requiring merely a voltage divider. Secondly, and more practically, the dimensions of the focus electrodes could be changed to give the same focus fields with the new focus electrodes at cathode potential as the originals gave at their optimum potential. This would also eliminate the secondaries which might reasonably be expected to improve operation still further if they have any effect on dc transmission. The transmission at design perveance is shown in Figure 32 as a function of beam voltage.

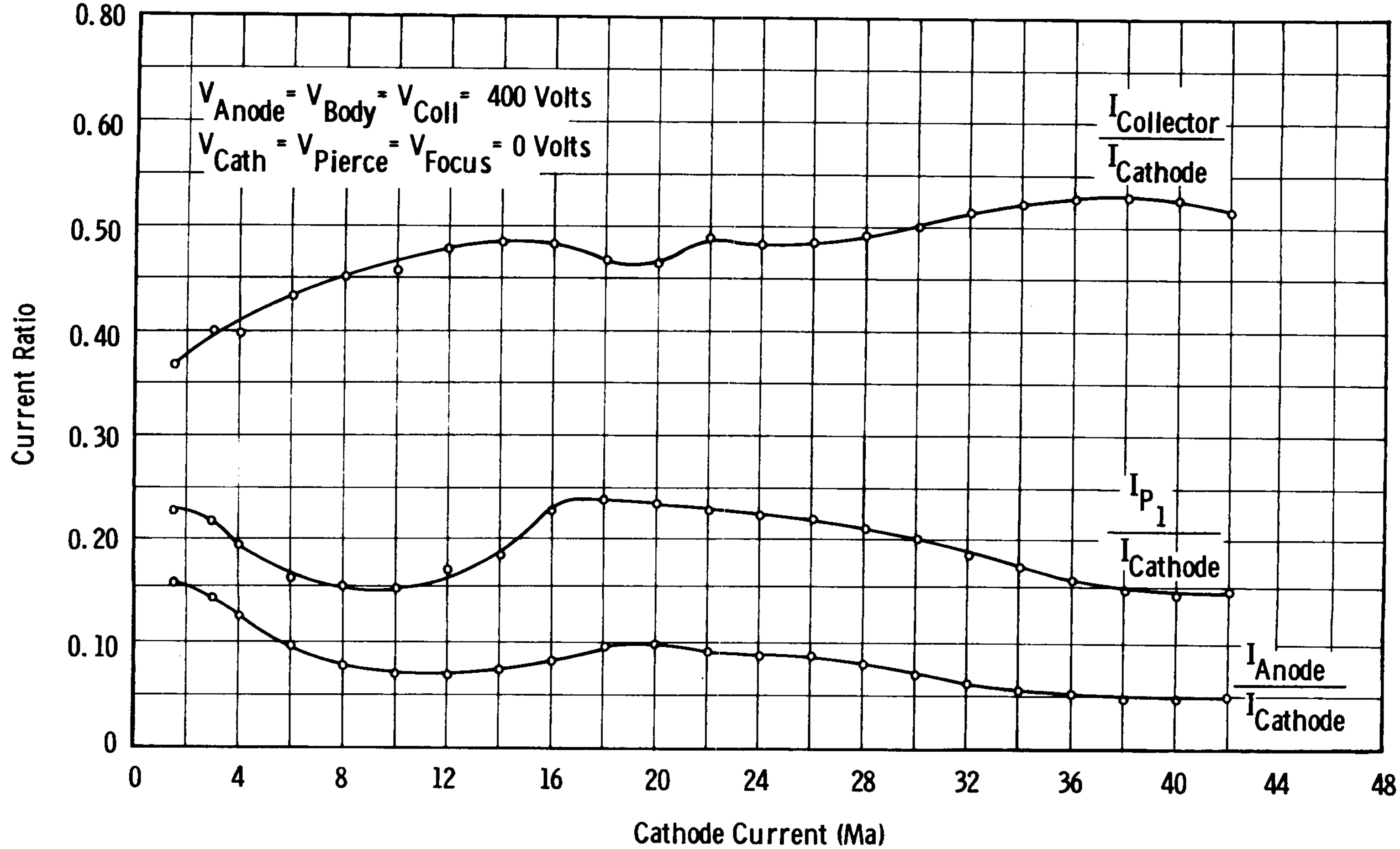



FIGURE 29
CURRENT DISTRIBUTION VS CATHODE CURRENT
FOR TEMPERATURE-LIMITED PERVEANCE
RANGE, BEAM TESTER B

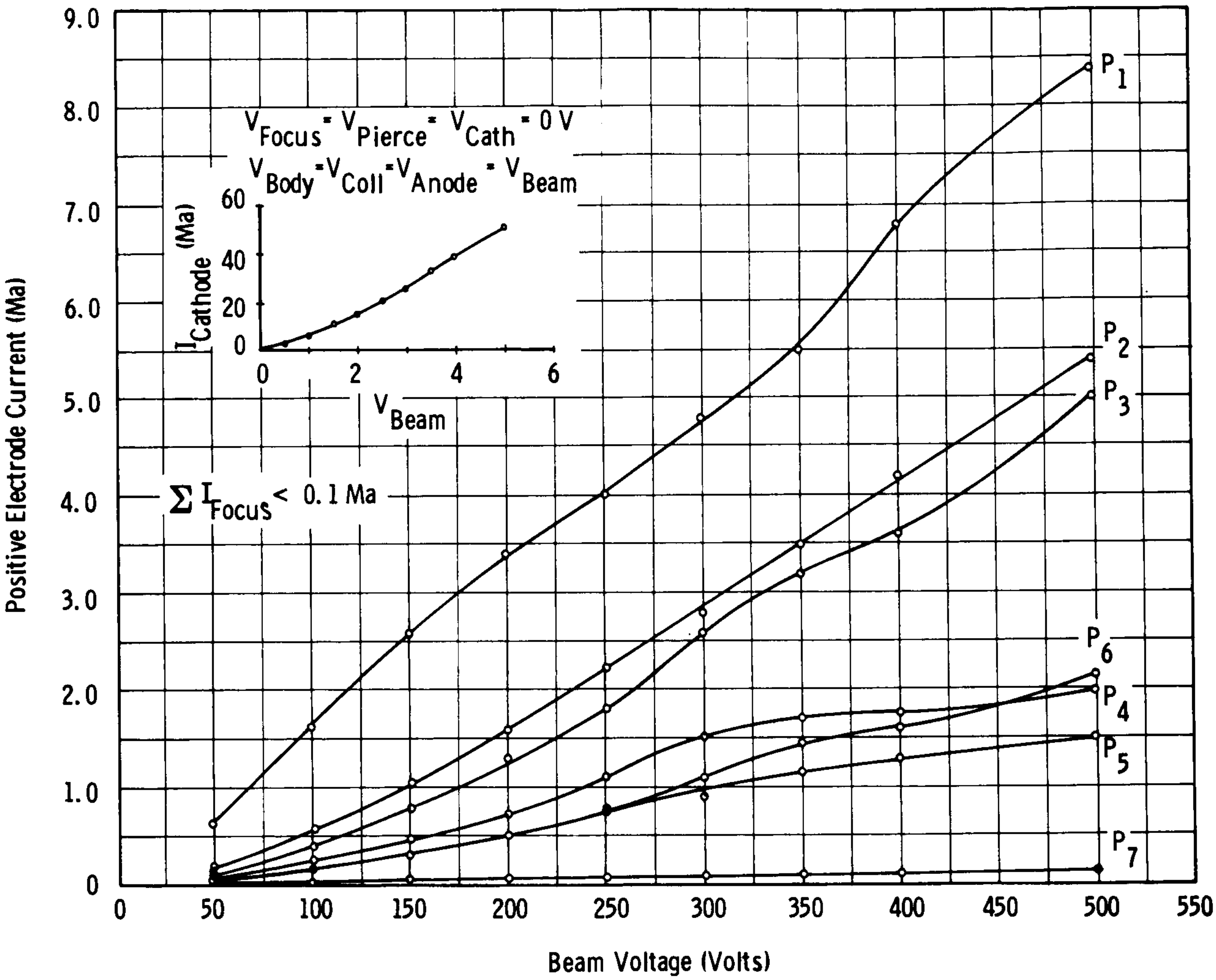



FIGURE 30
DISTRIBUTION OF BEAM CURRENT TO FOCUS ELECTRODES AS A FUNCTION OF BEAM VOLTAGE WITH $V_{Focus} = V_{Cathode}$, BEAM TESTER B

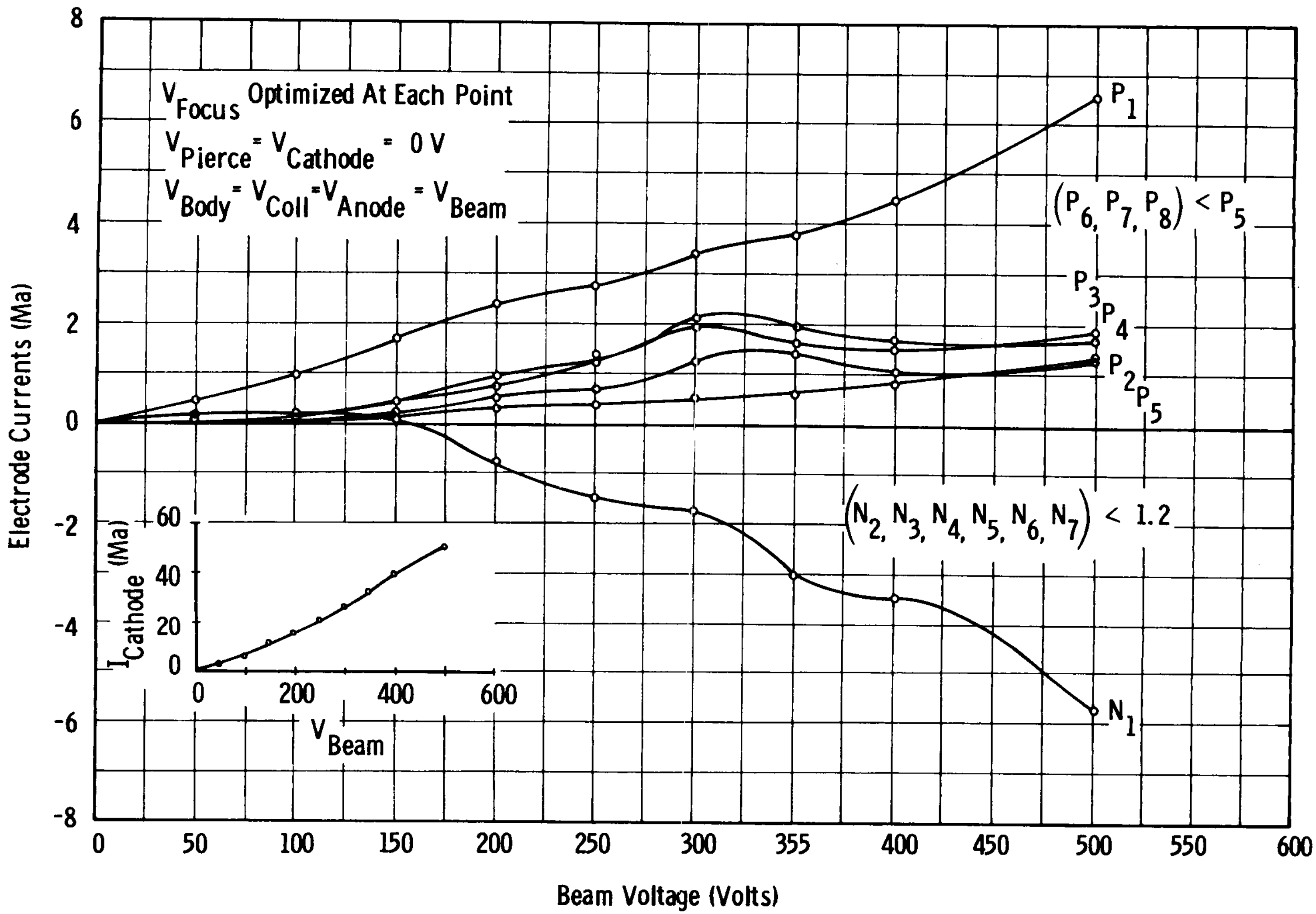



FIGURE 31
DISTRIBUTION OF BEAM CURRENT TO FOCUS ELECTRODES AS A FUNCTION OF BEAM VOLTAGE WITH $V_{Focus}$ OPTIMIZED AT EACH POINT, BEAM TESTER B

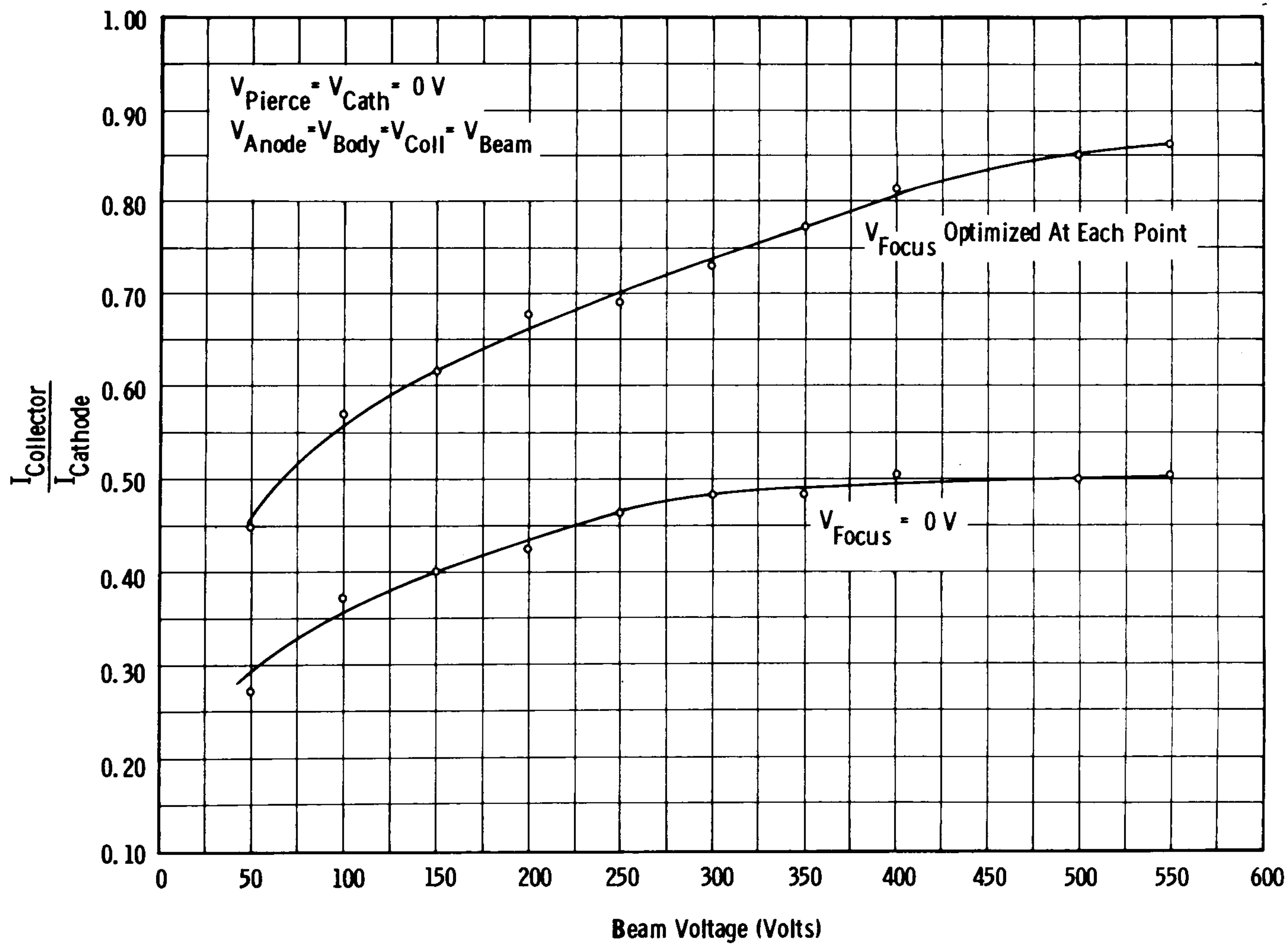



FIGURE 32
TRANSMISSION VS BEAM VOLTAGE AT DESIGN PERVEANCE
FOR $V_{Focus} = V_{Cathode}$ AND $V_{Focus}$
OPTIMIZED AT EACH POINT

## V. SUMMARY

A considerable effort was spent both in the design and proof of feasibility of the very close spaced, high voltage focusing structure which was required in this device. A very close spaced, well insulated, interdigital focusing structure occupying a minimum volume within the drift tubes was required and the fabrication and assembly technique for this was only perfected after several false starts. In particular the need to monitor edge effect current meant an extra side electrode and the resulting design required five sequential vacuum quality brazes. Although the techniques for doing this were known, the actual detailed sequence of processes required a great deal of time and effort to perfect. These mechanical aspects along with the mechanical and thermal design effort spent on the gun structure were more consuming of time and effort than had been envisioned and delayed the program progress considerably. These delays and the focusing difficulties caused in large part by mechanical alignment problems caused a re-direction of the program at about the two-thirds mark. At this time the fabrication of the 4 cavity test vehicle was almost complete, all parts having been made, the three drift tubes completely assembled, gun, collector and tuners completely assembled and final assembly to be the next step. The shortage of program time remaining and the focusing difficulties just discovered in the first bell jar experiments made it clear that the step from concept to 4 cavity tube was too large for the time and effort allocated.

The electrical design of the specified tube was completed and is felt to be satisfactory. The high perveance strip beam approach provided the high beam conductance necessary to meet the electrical specifications. The computer design of the gun and focusing structure as well as small signal gain-bandwidth analysis proceeded in a straightforward fashion. The hard-focusing concept worked well on paper at least and use was made of an approximation which allowed us to estimate the effect of rf bunching on the focusing. The approximation chosen was to increase the charge-density uniformly with distance along the length of the tube until the effective perveance was $18 \times 10^{-6}$, thus simulating 120° bunches.

The high efficiency aspects of the tube design were approached in two directions. The first approach, that of adiabatic bunching was found to be of no practical utility in this application. The second approach, that of variable collector depression and small drift tubes proceeded through the design stages and should perform well. The experimental phase did not reach this point and no verification by data is available.

The focusing experiments disclosed that structure alignment was very critical. Several relatively minor mis-alignments were corrected and dc transmission of a perveance $5.0 \times 10^{-6}$ beam increased from about 20% to 85%. By increasing body voltage above anode voltage a beam of perveance $1.5 \times 10^{-6}$ had over 95% transmission. It was found that the optimum focus voltage was less than that predicted. Maximum transmission occurred for focus voltages ranging from about $.5\ V_o$ to $.6\ V_o$. It is not yet clearly understood why this is the case. It was shown that edge effects are not of any serious consequence with current interception on the edges of less than 0.1% of cathode current for a well-aligned structure. Thus the complexity in construction caused by the inclusion of separate edge electrodes can be avoided in any future work.

The consistent improvement in dc transmission that accompanied successive experiments with the improving alignment indicates that the fundamental approach of a hard focused strip beam has considerable merit. It has also been shown that the fabrication of such a device is sufficiently complex that it might constitute an economic problem, even after development. This will not be established until such simplifications as will result from further developmental work become known.

# VI. RECOMMENDATIONS

Further programs in this area should be guided by the degree of need for this type of performance and should be balanced against the cost and feasibility of other possible techniques, such as PPM focused traveling wave tubes. Should it be determined that the advantages of the EFK warrant further developmental work on hard-focused strip beam tubes, the next steps should be characterized as applied research or advanced development.

1. Fabrication and testing of a multi-plate structure as shown in Figure 21 but scaled up by a factor of five to allow a better determination of allowable alignment tolerances.

2. Inclusion of rf voltage across the first gap and a repeat of a complete parametric mapping as in 1. above.

3. Computer simulation of mechanical abberations, to see if the computer can predict the interception caused by mis-alignment.

4. Computer simulation of the experimentally determined optimum focusing conditions.

5. Operation of the beam tester shown in Figure 21 as a two cavity klystron, with adjustable cavities, to study transmission through a saturated output gap, efficiency versus beam power and such other factors as show themselves to merit study.

6. Construction and test of a final tube designed to meet the electrical specifications.

7. Analysis of the results of the six steps outlined above with a view to determining what operating parameters and specifications are feasible for a final tube.

The advantages inherent in a high perveance EFK may well be realizable but a program of applied research and advanced development should precede any attempt at an operable tube.



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